CRANFIELD UNIVERSITY

Brian P. Lee

Pilot and Control System Modelling for Handling Qualities Analysis of Large Transport Aircraft

School of Engineering
Department of Aerospace Sciences
Dynamics, Simulation, and Control Group

PhD Thesis
Academic Year: 2011 - 2012

Supervisor: M. V. Cook
August, 2012

Frontispiece: Boeing 787 and 747-8 Intercontinental meet in the skies over Western Washington State

Both certified in 2011, the 747-8 is the latest and largest derivative of the conventionally designed 747 while the 787 is an all-new design featuring composite primary structure and fully integrated fly-by-wire control in all axes.
Photo courtesy of Boeing.

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ABSTRACT

The notion of airplane stability and control being a balancing act between stability and control has been around as long as aeronautics. The Wright brothers' first successful flights were born of the debate, and were successful at least in part because they spent considerable time teaching themselves how to control their otherwise unstable airplane.

This thesis covers four aspects of handling for large transport aircraft: large size and the accompanying low frequency dynamics, the way in which lifting surfaces and control system elements are modelled in flight dynamics analyses, the cockpit feel characteristics and details of how pilots interact with them, and the dynamic instability associated with Pilot Induced Oscillations.

The dynamics associated with large transport aircraft are reviewed from the perspective of pilot-in-the-loop handling qualities, including the effects of relaxing static stability in pursuit of performance. Areas in which current design requirements are incomplete are highlighted. Issues with modelling of dynamic elements which are between the pilot's fingers and the airplane response are illuminated and recommendations are made.

Cockpit feel characteristics are examined in detail, in particular, the nonlinear elements of friction and breakout forces. Three piloted simulation experiments are described and the results reviewed. Each was very different in nature, and all were designed to evaluate linear and nonlinear elements of the cockpit feel characteristics from the pilot's point of view. These included understanding the pilot's ability to precisely control the manipulator itself, the pilot's ability to command the flight path, and neuro-muscular modelling to gain a deeper understanding of the range of characteristics pilots can adapt to and why. Based on the data collected and analyzed, conclusions are drawn and recommendations are made.

Finally, a novel and unique PIO prediction criterion is developed, which is based on control-theoretic constructs. This criterion identifies unique signatures in the dynamic response of the airplane to predict the onset of instability.

Keywords:

Stability and Control, Flight Dynamics, Flying Qualities, Pilot Induced Oscillation (PIO),

DEDICATION

To Jonathan, Alexander, and Rebekah

I hope that in watching the process of producing this work you will have gained an appreciation for the importance of life-long learning.

ACKNOWLEDGEMENTS

The pursuit of a PhD represents a significant endeavour in time invested, in level of attention, and both over a protracted period of time. In preparation for this endeavour, many contributory opinions were offered by various colleagues whose opinions deserve a great deal of respect. In particular, the late Dr. John McMasters observed that there are only three valid reasons to pursue a PhD, and John was adamant that this question should be addressed and answered prior to launching the requisite effort:

- First, to prove to oneself that it can be done; rather like climbing a mountain.
- Second, if the credential is required for some larger pursuit; like teaching at the university level in the US.
- Third, if interest in a particular subject is so strong that pursuit of the PhD is the only legitimate way to justify the level of effort and depth of work.

Even after having invested more than a third of a century studying how pilots interact with airplanes, it was clear that there is still much to learn. It was therefore in this third pursuit that the present work is continued.

Having settled that question, it is recognized at the outset that no work of significance can be accomplished by one person alone, and this effort is no exception. A very special debt of gratitude is due to Mr. Michael Cook for sharing the fruits of his long and rich experience in flight dynamics and to his lovely wife, Helen for sharing him for this time. Mike’s depth of knowledge, his wisdom, and his unflappable demeanour have been a constant encouragement.

Technical collaboration brings huge benefits to all participants as each shares talent, insight, experience, and occasional flashes of genius with the other. In this case a debt of gratitude is due to many professional colleagues around the world, who have contributed via direct collaboration, active encouragement, acting as a sounding board, or just being interested. The list is too long to try to enumerate without risking the embarrassment of inadvertently overlooking someone. Nevertheless, there is special appreciation for the late Dr. Victor

Rodchenko, his successor Dr. Larisa Zaichik, and their colleagues at the Central Aero-Hydrodynamic Institute (TsAGI) of Russia. These extremely gifted individuals have served as a true inspiration. Appreciation is due also to Dr. Dale Hiltner for sharing both his insights and his frustrations during our development of the Dynamic Oversteer Criterion. Special insights and inspiration have been derived from long associations with John Hodgkinson, Dave Klyde, Dave Mitchell (all of the "Handling Qualities Daves", really), Roger Hoh, and the late Robert Wattson.

Any technical and academic endeavour requires extensive use of archival information. Thanks are due to the dedicated professional librarians, both at Cranfield and at the Boeing company for providing valuable assistance. I have never experienced university library staff so eager to offer such professional assistance as I found at Cranfield. In an industrial setting, the thoroughly professional staff of the Boeing library understand the special requirements of this kind of technical work and recognize the value to the company of providing technical staff with the best support in the world.

Thanks also to the management of The Boeing Company for allowing the special privilege of studying this subject over this protracted period.

Finally, very special thanks to Susan for her domestic contributions which were essential to the completion of this work.

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NOMENCLATURE

Preamble

Abzug and Larrabee (1997) point out that even though special notation for use in the equations of motion of aircraft has been in use since the earliest treatments of the subject, standardization of the notation itself has remained ellusive. The Engineering Sciences Data unit of the Royal Aeronautical society recommended a new set of standards for nomenclature as part of a 1967 review of the subject. This recommendation followed on the impressive work of Hopkin (1966) which made an attempt to accommodate the already proliferating nomenclature. Abzug and Larrabee (p. 259) quote Hopkin:

> “Notation is an extension of language, and a Tower of Babel should not be allowed to grow.”

In the United States, NACA, from the very first year of its inception recognized the need for standardized nomenclature (NACA (1916)), and by it’s second year had published its first standard (NACA (1917)). The standard has been revised several times in the nearly 100 years since, see e.g. Charters (1955), Gainer and Hoffman (1972), McFarland (1975). International efforts show very different nomenclature around the world. Authors in the UK have produced “glossaries” of terms to help readers make the mental leap between systems (See, e.g. Cook, 2007, Duncan,1952). Beyond nomenclature, experience shows that fundamental assumptions about things like reference axes are not standard world-wide, either: In the US and Europe, reference axis systems are defined using a Right Hand Rule ([+X, +Y, +Z] = [Forward, Right, Down]). Russian colleagues (Busgens and Studnev, 1979) have their own standards, which while incorporating the familiar Right Handed orientation, have principal axes rotated 180 degrees around the X-axis from the Western tradition, resulting in: ([+X,+Y,+Z] = [Forward, Left, Up]. Microsoft Flight Simulator is built on a fundamental assumption using *a Left Hand Rule*. (Zyskowski, 2003) Finally, an international effort by the AIAA Atmospheric Flight Mechanics Technical Committee in which this author participated in the early 1990’s produced an AIAA standard (AIAA, 1992), which similarly did not catch on and was subsequently withdrawn. Each organization seems to adopt its own convention; Abzug and Larrabee opined that

> "Authors apparently are content to define symbols that are clear enough in the context of their work". (p. 259)

This work borrows liberally from the work of others on the subject. No attempt has been made to convert the work of others to present a "standard" nomenclature. Instead, the view of Abzug and Larrabee prevails. As a result, some of the nomenclature here might seem confusing and duplicative. It is, however, only a manifestation of the state of the industry. By providing definitions of the nomenclature quoted and used, the intent is to aid in unifying the concepts presented by many diverse authors.

Roman Alphabet

A	mass
A	Constant (e.g. initial displacement)
A, B, C, D, E, F,	Points on force vs deflection plot to define Linearity Index (LI)
A_i	Forcing function input amplitude at each frequency
A_f	Disturbance function input amplitude at each frequency
b	Base of parallelogram
B	Damping coefficient
Br	Breakout force
c	Dimensional damping constant
$\bar{c}_e$	Elevator aerodynamic chord
C	Spring constant
C_D	Trimmed drag coefficient
C_{h_e}	Elevator hinge moment coefficient
C_L	Trimmed lift coefficient
e	Tracking error
e	The exponential function
f	Index for frequencies in disturbance input function

f	Forcing function
F	force
F_{br}	Breakout force
F_{fr}	Friction force
F_m	Maximum force
$F_{\min_{1/2}}$	Minimum force at Level 1 / Level 2 boundary
$F_{\max_{1/2}}$	Maximum force at Level 1 / Level 2 boundary
$F_{\max_{2/3}}$	Maximum force at Level 2 / Level 3 boundary
F_{nz}	Derivative of force with respect to load factor
F_{per}	Permissible value of control force
F_r	Friction force
F_{r*}	normalized friction force
F_*	Optimum value of control force
$\overline{F}$	Pilot applied forced
F_δ	Derivative of force with respect to deflection
$F_{\dot{\delta}}$	Derivative of force with respect to control displacement rate
g	Gravitational constant
G	Gearing constant
h	Height of parallelogram
HM	Aerodynamic hinge moment
i	$\sqrt{-1}$
I	Input to tracking task
I_y	Mass moment of inertia about the y axis
j	$\sqrt{-1}$
k	Spring constant
$k_F, k_\Delta, k_\delta, k_{t_r}$	Constants
K	Gain coefficient
K_c	Gain coefficient
K_{cns}	Gain coefficient
K_{ns}	Gain coefficient
K_p	Gain coefficient
$\mathscr{L}$	Laplace operator
LI	Linearity Index
l_1, l_2	Input arm lengths for hydraulic actuator
m	Index for frequencies in forcing function
m	mass
m_q	Concise derivative of aerodynamic pitching moment with respect to pitch rate

m_u	Concise derivative of aerodynamic pitching moment with respect to forward velocity
m_w	Concise derivative of aerodynamic pitching moment with respect to vertical velocity
m_η	Concise derivative of aerodynamic pitching moment with respect to elevator deflection
m_θ	Concise derivative of aerodynamic pitching moment with respect to pitch attitude
M1LI	Modified linearity index, mod 1
M2LI	Modified linearity index, mod 2
M_q	Derivative of aerodynamic pitching moment with respect to pitch rate
$\overset{o}{M}_q$	Dimensional derivative of aerodynamic pitching moment with respect to pitch rate
M_u	Derivative of aerodynamic pitching moment with respect to forward velocity
$\overset{o}{M}_w$	Dimensional derivative of aerodynamic pitching moment with respect to vertical velocity
M_α	Derivative of aerodynamic pitching moment with respect to angle of attack
$M_{\dot{\alpha}}$	Derivative of aerodynamic pitching moment with respect to angle of attack rate
M_{δ_e}	Derivative of aerodynamic pitching moment with respect to elevator deflection
n	Load factor
n_e	Pilot remnant
n_i	Integer multiplier on frequency in forcing function
n_x	Limb-manipulator remnant
p	Perturbation roll rate
p_0	Perturbation roll rate initial condition
p_*	Characteristic roll rate
q	Perturbation pitch rate
$\bar{q}$	Dynamic pressure
$\bar{q}_e$	Trimmed dynamic pressure
$\bar{q}_e$	Dynamic pressure at the elevator
$\dot{q}$	Time derivative of pitch rate
r	Perturbation yaw rate

r_0	Perturbation yaw rate initial condition
s	Laplace operator
S_e	Elevator area
t	time
t_{r^*}	Optimum value of response time
t_r	Feel system response time
t_{per}	Permissible value of response time
T	Time constant
T_l	Lag time constant
T_L	Lead time constant
$T_{ns_1}, T_{ns_2}, T_{ns_3}$	Time constants
T_1, T_2	Time constants
T_2	Time to double amplitude for an unstable system
u	Perturbation forward velocity
$\dot{u}$	Time derivative of forward velocity
U_e	Equilibrium forward velocity
U_1	Initial forward velocity
v	Perturbation side velocity
$\dot{v}$	Time derivative of side velocity
v_0	Perturbation side velocity initial condition
V_T	True airspeed
V_0	Trimmed total velocity
w	Perturbation vertical velocity
$\dot{w}$	Time derivative of vertical velocity
$\bar{x}$	Displacement
$\dot{x}$	Time derivative of displacement; velocity
$\ddot{x}$	Second time derivative of displacement; acceleration
x_q	Concise derivative of aerodynamic force in the X direction with respect to pitch rate
x_u	Concise derivative of aerodynamic force in the X direction with respect to forward velocity
x_w	Concise derivative of aerodynamic force in the X direction with respect to vertical velocity

x_η	Concise derivative of aerodynamic force in the X direction with respect to elevator deflection
x_θ	Concise derivative of aerodynamic force in the X direction with respect to pitch attitude
X	displacement
X	Axis label for longitudinal axis
X_q	Derivative of aerodynamic force in the X direction with respect to pitch rate
X_u	Derivative of aerodynamic force in the X direction with respect to forward velocity
$X_{\dot{w}}$	Derivative of aerodynamic force in the X direction with respect to vertical velocity rate
X_α	Derivative of aerodynamic force in the X direction with respect to angle of attack
X_{δ_e}	Derivative of aerodynamic force in X direction with respect to elevator deflection
y	displacement
Y	Axis label for lateral axis
Y_c	Airplane transfer function
Y_{cns}	Central nervous system transfer function
Y_{fs}	Feel system transfer function
Y_{lm}	Limb-manipulator transfer function
Y_{ns}	Neuro-muscular system transfer function
Y_p	Pilot transfer function
z_q	Concise derivative of aerodynamic force in the Z direction with respect to pitch rate
z_u	Concise derivative of aerodynamic force in the Z direction with respect to forward velocity
z_w	Concise derivative of aerodynamic force in the Z direction with respect to vertical velocity
z_η	Concise derivative of aerodynamic force in the Z direction with respect to elevator deflection

z_θ	Concise derivative of aerodynamic force in the Z direction with respect to pitch attitude
Z	Axis label for vertical axis
Z_q	Derivative of aerodynamic force in the Z direction with respect to pitch rate
Z_u	Derivative of aerodynamic force in the Z direction with respect to forward velocity
$Z_{\dot{w}}$	Derivative of aerodynamic force in the Z direction with respect to vertical velocity rate
Z_α	Derivative of aerodynamic force in the Z direction with respect to angle of attack
$Z_{\dot{\alpha}}$	Derivative of aerodynamic force in the Z direction with respect to angle of attack rate
Z_{δ_e}	Derivative of aerodynamic force in the Z direction with respect to elevator deflection

Greek Alphabet

α	Angle of attack
α	Damping constant
α	Parallelogram skew angle
β	Characteristic angular frequency
β_0	Undamped angular frequency
γ_0	Perturbation flight path angle initial condition
δ	Angular control displacement
$\bar{\delta}$	Controller displacement
$\tilde{\delta}$	Dimensionless deflection
$\dot{\delta}$	Time derivative of angular control displacement
$\ddot{\delta}$	Second time derivative of angular control displacement
δ_e	Elevator deflection
δ_m	Maximum deflection
δ_p	Deflection at a particular roll rate
δ_*	Optimum value of displacement
δ_{per}	Permissible value of displacement
δ_{pilot}	Assumed pilot input (deflection)
δ_{nz}^*	Reference derivative of control deflection with respect to load factor
δ_{nz}	Derivative of control deflection with respect to load factor
δ_0	Initial deflection
Δ	Indicates a change; a perturbation
Δ	Feel system overshoot
Δ_{ns}	Depth of the “dip” in neuro-muscular transfer function
Δ_{per}	Permissible value of overshoot
Δ_*	Optimum value of overshoot
ζ	Damping ratio
ζ_{ns}	Damping ratio
ζ_p	Damping ratio of the phugoid mode
ζ_{sp}	Damping ratio of the short period mode
ζ_1	Damping ratio
η	Elevator deflection
θ	Perturbation pitch attitude
θ_1	Initial pitch attitude

$\dot{\theta}$	Time derivative of pitch attitude
ρ	Atmospheric density
ρ_c	Magnitude from initial condition in modal solution
ρ_υ	Magnitude of the eigenvector in modal solution
σ	Magnitude of eigenvalue in modal solution
τ	Dimensionless time
τ	Inverse time constant
τ_{cns}	Time constant
τ_{ns}	Time constant
τ_r	Roll mode time constant
τ_{θ_p}	Pitch attitude phase delay parameter
τ_1	Inverse time constant
ϕ_c	Phase angle from initial condition in modal solution
ϕ_0	Perturbation roll attitude initial condition
ϕ_υ	Phase angle of the eigenvector in the modal solution
φ	Phase angle
φ	Visual field of view
ψ	Heading angle
ψ	Phase angle
$\dot{\psi}$	Heading rate
ω	Circular frequency
ω	Phase angle of eigenvalue in modal solution
$\omega_{c_{lm}}$	Crossover frequency of limb-manipulator system
ω_d	Damped frequency
ω_n	Undamped natural frequency
ω_{ns}	Frequency of the “dip” in neuro-muscular transfer function
$\omega_{n_{sp}}$	Undamped natural frequency of the short period mode
ω_p	Frequency of the phugoid mode
ω_{sp}	Short period natural frequency

Acronyms and Abbreviations

AGARD	Advisory Group for Aerospace Research and Development, the technology arm of the North Atlantic Treaty Organization, predecessor to RTO
AIAA	American Institute of Aeronautics and Astronautics
APC	Airplane-Pilot Coupling. In some author's vernacular, this refers to classic Pilot Induced Oscillation (PIO). In others, notably, Boeing Commercial Airplanes (Seattle), APC refers to a phenomenon in which the pilot is holding the controls and is involved in driving the dynamic motion which itself is dominated by structural dynamics. In this distinction, the pilot is coupled to the airplane, but only passively. That is, the pilot is not necessarily trying to move the controls to effect the motion of the airplane. The motion imparted to the controls (which is driving the dynamic motion) is rather involuntary on the part of the pilot. Other authors have referred to this phenomenon as Bio-dynamic coupling, bio-kinematic coupling, or in the case of Calspan, the mannequin effect.
CG	Centre of gravity, usually specified as fraction of Mean Aerodynamic Chord, (MAC).
CS25	European certification standard, Part 25 for transport category aircraft.
EASA	European Aviation Safety Authority. Unlike JAA, EASA is a stand-alone agency, under the European Union who now has authority for aviation safety in Europe. EASA came into being via regulation of the European Commission in 2002.
FAA	Federal Aviation Administration in the United States
FOV	Field Of View, horizontal
HQR	Handling Qualities Rating, usually a rating on the Cooper-Harper Handling Qualities Rating Scale.
HQRM	Handling Qualities Rating Method. This is the FAA's means for finding compliance with certification requirements, mostly used for failure conditions (and PIO).
JAA	Joint Aviation Authority, formerly the oversight agency for aviation safety in the European Union. Actually, JAA was a collaboration of the individual aviation regulatory authorities of the various member states, not an independent agency.

LI Linearity Index

MAC Mean Aerodynamic Chord [defn]

MCP Mode Control Panel for the autopilot

NRC National Research Council in the United States.

PIO Pilot Induced Oscillations. Also Pilot Involved Oscillations as authors sought to soften the "blame" placed on pilots for being party to the dynamic instability. For the same reason, some authors refer to this phenomenon as Airplane-Pilot Coupling (APC). For others, APC means something different, see APC

PR Pilot Rating, in particular, Cooper-Harper rating.

RTO Research and Technology Organization, the primary NATO organization for defense science and technology.

QSAE Quasi-Steady Aeroelastic, a modelling assumption under which the time-dependent unsteady lift is ignored and aerodynamic forces are assumed to be generated instantaneously. While dynamic elastic motion is ignored, many times, static elastic effects are accounted for.

SOP Successive Order of Perception, a hierarchy of control architectural patterns, or control strategies pilots use.

V_{DF}/M_{DF} Maximum speed (V), or Mach (M) "Demonstrated in Flight", a structural design speed which must be demonstrated in flight test for certification.

V_{FC}/M_{FC} Maximum speed/Mach for "Flight Characteristics". Usually half way between Vmo/Mmo and V_{DF}/M_{DF}, unless effective speed warning is present, this is the highest speed that normal flight characteristics must be shown to.

Vmo/Mmo Maximum Operating Speed (V) or Mach (M). Constitutes a limitation for pilots.

14CFR25 Part 25 of Title 14 of the US Code of Federal Regulations: the certification standard for transport category aircraft.

1 Introduction

> Show me a man who is not confused and I will show you a man who has not been thinking. He will be a man who has not asked enough questions… There will always be more questions than thoughtful men can answer, though the unreflective, to be sure, will always have their fast answers ready. The essence of intellect is in the engagement of proliferating confusion.
>
> John Anthony Ciardi[*]

> He that would make real progress in knowledge must dedicate his age as well as his youth, the latter growth as well as the first fruits, at the altar of truth.
>
> Bishop George Berkeley[†]

Early on in their course of study, students of Aeronautics learn that the aerodynamics sub-discipline of *Stability and Control* is really the separate but interconnected study of two subjects: one being *Stability*; the other, *Control*. Further, they quickly learn that these two constructs are frequently at odds with each other: Stability tends to resist motion, while response to controls is such as to induce motion. Ease and precision of manoeuvring speaks directly to the balance between these two; the conjunction of stability and control and, with the addition of a human pilot to do the controlling, the rise of the new discipline: Handling Qualities.

Understanding of these connections was not always obvious. In fact, the understanding evolved along with the development of the vehicles themselves and the evolution took quite a long time. Even decades after the first human flight, at the end of World War I, when the airplane was in common usage, it was still not obvious, and it would take another 25 years or so for the aeronautics community to come to consensus.

[*] John Ciardi was an American poet, translator, and etymologist. These words first appeared in an essay entitled "The Courage of His Confusions" in the *Saturday Review*, 2 June, 1962. It was reprinted in his book "Manner of Speaking" (Ciardi, 1972).

[†] Bishop George Berkeley was an Anglo-Irish philosopher who had at one time argued against the foundations of infinitesimal calculus and Newton's doctrine of absolute space, time, and motion. This quotation, however, was penned some thirty years after those arguments in his "Siris: A chain of Philosophical Reflexions and Inquiries", first published in 1744 (Campbell, 1901).

With the coming of new technologies and new applications of old technologies, these connections are still evolving, and still evolving slowly in the manner described by Vincenti (1990).

1.1 The many elements of Handling Qualities.

The pilot's task in flying a modern jet transport aircraft can be represented by a number of functions, across various levels of decision-making. These decisions range from those of a strategic nature to tactical decisions and many in between. The pilot must manage a complex system-of-systems and is many times free to decide how much automation to use or when to manually control the airplane. Just how humans go about this process has been considered by Jens Rasmussen via his Skills-Rules-Knowledge model. (Rasmussen, 1983). Rasmussen described the human operator behaviour through three distinct levels, as depicted in Figure 1-1. At the lowest level, that of skill-based behaviour, the pilot makes use of sensory input, identifies features or patterns in the inputs and performs essentially automated processes in response. This is a learned behaviour based on acquired skills and the information is passed via signals. The point of much pilot training is to instil in the pilot a learned set of responses to specific features so that the pilot does not have to think about how to accomplish the task. The control inputs become automatic and second nature.

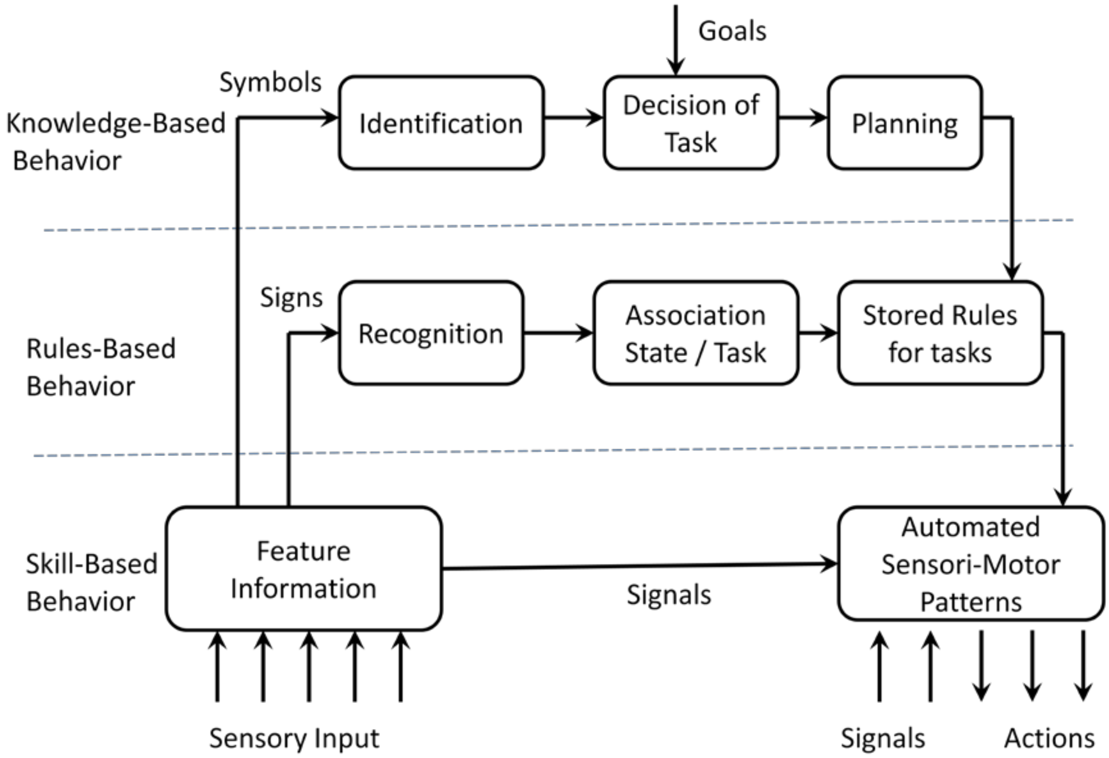

Figure 1 -1. Human Operator Behaviour Classifications, after Rasmussen (1983).

In rules-based behaviour, the pilot recognizes signs in the environment, associates a state or task with a sign, and then accesses a stored rule for conducting an appropriate task. This is a learned behaviour, but does not necessarily involve particular skills. Similar to skill-based behaviour, though, in order for the pilot to be effective in rule-based behaviour, he must 1) know the rules; and 2) be able to identify a control strategy in response. Also similar to skill-based behaviour, much of pilot training consists of providing the pilot with an acceptably large repertoire of responses to rules and signs so that when the signs are recognized, the proper control strategy can be implemented.

In knowledge-based behaviour, the pilot identifies symbols in the environment, which, in association with known goals invokes a planning process which acts through the learned rules. This can be illustrated by a trip-planning process, described below, but it is important to point out that if the pilot encounters a situation for which 1) the signals-to-automatic response does not seem to work, or 2) the signs are not recognized, the pilot must revert to knowledge-based behaviour to develop a plan of action (the rare-emergency scenario).

To illustrate these levels, consider a pilot's planning and flying a routine flight. The pilot recognizes a goal to fly from point A to point B. Using his knowledge of the navigational environment, and the symbols involved (perhaps a set of established airways between the two points), the pilot begins a planning exercise to establish a nominal track. At each waypoint, there may be regulations requiring, for example, specific altitudes to be flown. These rules are invoked via signs, perhaps notations on the navigation chart. Upon arriving at a designated waypoint, the pilot recognizes the need to change altitudes based on a set of stored rules. This altitude change is then put into action as a prescribed, probably memorized set of control inputs (in a pilot-closed loop sense) perhaps involving a change to throttle setting, and/or an input to the Mode Control Panel (MCP) of the autopilot.

The three levels of behaviour noted by Rasmussen are invoked rather continuously throughout a flight, as the pilot encounters various situations both normal and abnormal. In terms of just how this implementation is accomplished, consider a set of nested control loops, as in Figure 1-2, with skills-based behaviour appearing in the attitude stabilization loop, rules-based behaviour appearing in the manoeuvring loop, and knowledge-based behaviour appearing in the navigation and guidance loop.

Recalling that Handling Qualities is concerned with the collaboration between the pilot and the airplane's dynamics, it becomes clear that most of this collaboration takes place in the realm of skills-based behaviour. Just how that skills-based behaviour gets invoked and the architectural elements involved has been studied for decades, and is still ripe for better understanding. Pilots refer to this skill-based behaviour as "airmanship".

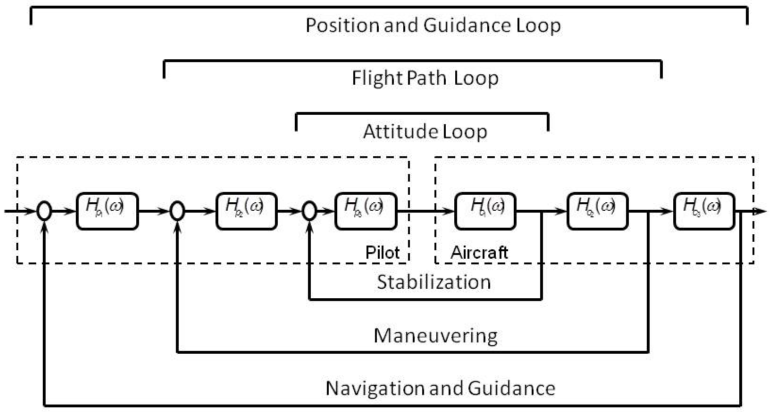

Figure 1-2 Rasmussen's functions in terms of pilot loop closure.

The ability to operate an airplane safely and efficiently requires the coalescence of a set of motor skills and behaviours guided or supported by knowledge. The FAA in its Airplane Flying Handbook (FAA, 2004) describes:

> "Every airplane has its own particular flight characteristics. The purpose of primary and intermediate flight training, however, is not to learn to fly a particular make and model airplane. The underlying purpose of flight training is to develop skills and safe habits that are transferrable to any airplane." (p. 1-1)

That training, combined with that outlined by FAA Advisory Circular 61-89E (FAA, 2000) is intended to produce the required repertoire of learned skill-based behaviours AND the necessary analysis capability and judgment to be able to recognize the symbols, signs, and signals suggested by Rasmussen's hierarchy to be able to move up and down between skill-based, rules-based, and knowledge-based, behaviours. This construct has been recognized by Kern (1996) as fundamental to the essence of airmanship.

In addition to a sound acquaintance with the principles governing flight itself and of the operation of various airplane systems, the pilot must learn to exercise sound judgment. As stressed by the FAA handbook, judgment consists of the ability to assess a situation quickly and accurately analyze the probable results of given circumstances or proposed procedure. This entails the ability to read the symbols, signs, and signals and know when to implement the learned motor skills. This operational knowledge has been linked directly to being essential in flight safety (FAA, 1980).

Regarding the development of motor skills required to operate an airplane, the FAA handbook goes on to describe several elements which it is essential that the pilot learn (2004, p. 1-1)

- "Coordination – the ability to use the hands and feet together subconsciously and in the proper relationship to produce desired results in the airplane.
- Timing – The application of muscular coordination at the proper instant to make flight, and all manoeuvres incident thereto, a constant smooth process.
- Control touch – The ability to sense the action of the airplane and its probable actions in the immediate future, with regard to attitude and speed variations, by sensing and evaluation of varying pressures and resistance of the control surfaces transmitted through the cockpit flight controls.
- Speed sense – The ability to sense instantly and react to any reasonable variation of airspeed."

There are some key words and phrases in these elements which have a direct bearing on the flight dynamics and handling qualities design of the airplane:

"Coordination" and "timing": use of hands and feet together in the proper relationship and at the appropriate times speaks directly to what flight dynamics engineers refer to as "phase angles" between the motion of different modes and in different axes.

"Subconscious" implies perhaps a learned behaviour, but it also brings to mind the notion that some behaviours might be easier to learn than others.

"Control touch" and "speed sense" suggest the importance of cockpit feel systems.

Each of these elements will be seen to be important in what is to follow.

1.2 Open Loop / Closed Loop and Sometimes in Between

The particular control strategy chosen by a pilot in any particular flight condition depends on a number of factors, not least of which is the specific task at hand and the desired level of performance. McRuer (1995) discusses that:

> "In essence, human adaptive and learning attributes permit the pilot to be simultaneously engaged as the on-going architect and modifier of the pilot-aircraft system itself and as an operating entity within that system. As the pilot "changes" the system organization, the pilot's dynamic behaviour is adjusted as appropriate for the overall system. This repertory of behaviour is so extensive that the pilot, as a learning and adaptive controller operating with an extensive array of endogenous sensing mechanisms, has capabilities which far exceed those of the most sophisticated unmanned control system." (p. 14)

McRuer goes on to identify a number of "control architectural patterns" which are particular types of pilot-vehicle structures which a pilot may choose to engage along with the transitions between those patterns which McRuer identifies as the "Successive Organization of Perception", or SOP. These patterns are:

- Compensatory: Pilot Response Conditioned on Errors
- Pursuit: Response conditioned on Errors + System Inputs and Outputs
- Pursuit with Preview: Preview of Input Added
- Precognitive / Compensatory: Dual Mode Control
- Precognitive: Skilled, Essentially Open-Loop

The SOP progressive transitions between these are identified as:

Compensatory
⇩ ⇧
Pursuit
⇩ ⇧
Precognitive/compensatory
⇩ ⇧
Precognitive

McRuer also notes that regressive transitions are possible, as are transitions induced by the controlled element, and these may include post-transition retention and re-adaption of specific control strategies. While it is difficult to discern just which strategy a pilot is using at any given time, or why – pilots themselves often cannot describe it - , Myers, McRuer, and Johnston (1984) note that pilots have at times been observed using a hybrid “intermittent control” strategy. There is some evidence that pilots are *compelled* to use one or another strategy by the dynamics of the airplane they are controlling and the mission task they are flying.

1.3 The Pilot’s Challenge

Figure 1-3 gives a control-theorist’s view of how a pilot interacts with the airplane and its controls in flying a particular task. In this depiction, the pilot occupies the biggest box, and is situated in the centre. This is a reminder of the critical nature of the pilot’s involvement in manoeuvring the airplane. The pilot knows what the task is and finds himself as an active element in the control loop, both regulating against disturbances and manoeuvring along a prescribed path. The pilot manipulates the control inceptor, getting feedback from it, while closing a loop around the flight path, getting visual and kinaesthetic feedback at the same time. Each element in that control loop contributes to the pilot’s ability to manoeuvre the airplane smoothly and precisely.

The pilot’s challenge is to achieve the specified task performance via the loop closure. Just when to progress through McRuer’s steps, and how deeply to go at any stage is the subject of the learning process involved in gaining Rasmussen’s repertoire of skills. The skills themselves, though, are largely defined by the characteristics of the airplane. The character of the airplane’s dynamic response to the pilot’s control inputs is what will define what the pilot needs to learn to produce an efficient and useful collaboration with the airplane.

Moreover, commercial jet transports are flown by a wide population of pilots with a wide range of inherent skill sets. Initial and recurrent training is expensive, so it becomes incumbent on the designer to understand those dynamic characteristics which are helpful and those which are not.

What began as the “pilot’s challenge” has thus become the “engineer’s challenge” as well. Figure 1-3 was constructed from a number of blocks deliberately because these represent the models which can inform a collaboration between pilot and designer, with the airplane or its constituent models in the middle (i.e. between the pilot and the designer).

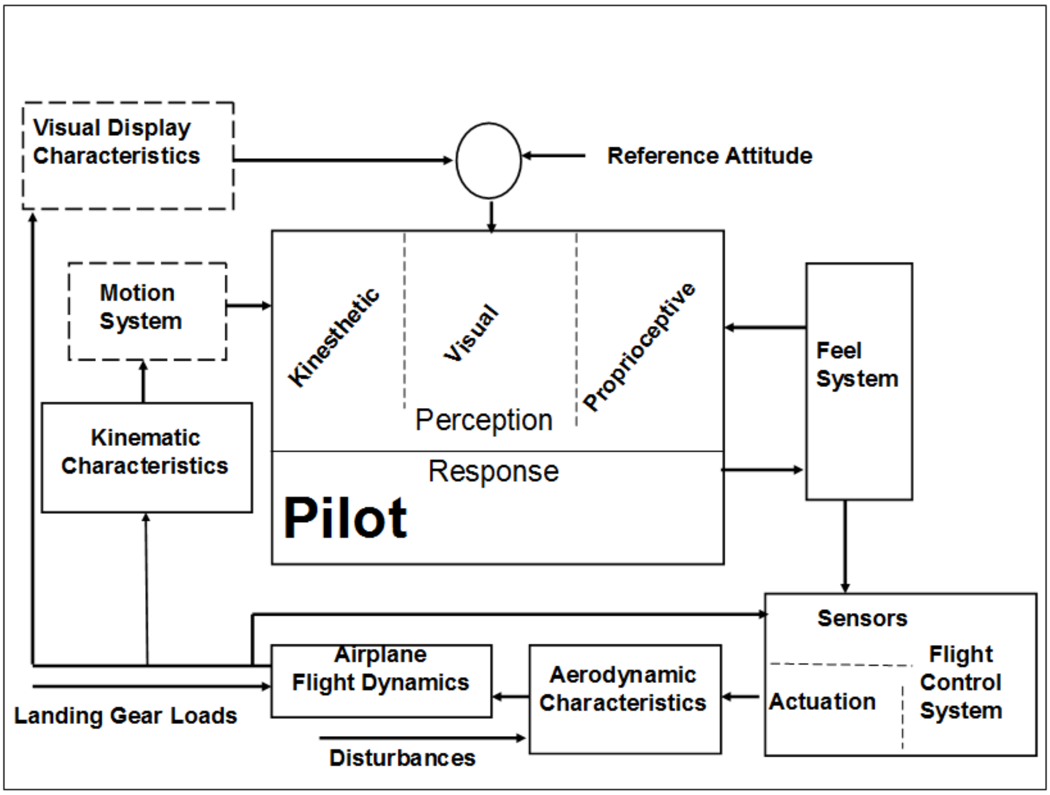

Figure 1-3. The Pilot’s Challenge

1.4 Models and Frequencies of Interest

Humans are amazingly adaptive controllers, but there are limits, and the human’s preference for particular frequency ranges frequently shows up in flying technique and quantitative analysis of manoeuvre performance. Moreover the human’s ability to move between and among the patterns of behaviour noted by McRuer may well be limited by the response dynamics of the vehicle being controlled. It will be seen in Chapters 3 and 4 that humans behave differently with vehicles which respond at very low frequencies than they do with vehicles capable of responding at higher frequencies.

As airplanes have grown larger, heavier, and faster, their dynamics have taken on a unique character which have impact on the ability of the pilot to engage in closed-loop control. Large transport aircraft are unique in that being large, they exhibit relatively slow natural frequencies, but even on final approach, the pilot finds himself approaching the concrete at perhaps 140 knots, a situation imposing urgent demands on the pilot.

A number of characteristics have been identified which contribute to (or detract from) favourable pilot closed-loop behaviour. The characteristics discussed are not *necessarily* unique to large transport aircraft, but are present in them, and each tends to move in a direction away from harmony with a human controller as airplane size increases. Moreover, the way in which these characteristics are modelled is important to understanding the pilot-vehicle relationship.

- Large physical size.
  Modern jet transport aircraft are physically large, and come with sizeable inertia. One result of that combination is that the characteristic dynamics of motion is comparatively slow. The natural frequencies of motion vary inversely with physical size.
- Transients in dynamic response to control inputs.
  The detailed character of the transient dynamic response of an airplane to control inputs can be critical for the pilot's ability to control the path of the airplane. As airplanes grow in size and natural frequencies diminish, some details of the transient become more visible. Others may fall below perception thresholds.
- Relaxed static stability.
  Relaxing the static stability, by pushing the centre of gravity aft or by reducing the size of the horizontal tail, or both, has significant economic benefits. While there is a reliance on modern flight control to restore effective stability, care must be taken that the control system details are attended to properly.
- Limitations of quasi-steady aerodynamics assumption.

Flight dynamicists have typically modelled the aerodynamic force and moment generation capability of airplanes using assumptions of "quasi steady flow". It will be seen that the effects of the quasi-steady assumption are a function of airplane physical dimensions.

- Actuators and the way they are modelled.
  One consequence of large physical dimensions and which is complicated by large speed ranges is the need for powered actuation of flight control surfaces. Typically used hydraulic actuators exhibit characteristics which if not modelled properly will result in the appearance of unexpected time delays in the response to control inputs.
- Cockpit pilot feel systems
  A consequence of the introduction of hydraulic actuators to move flight control surfaces is the need for artificial control feel. This provides the pilot with critical feedback, but the details of practical design of the system is often not given due attention.

1.5 The Role of the Pilot

The role of the pilot and the dynamic interaction with these elements is at the heart of handling qualities. This is different from the "Pilot's Challenge" described above. In this sense, the role of the pilot is to aid our understanding of the dynamic interactions between airplane and pilot. Detailed models of human pilot behaviour can help illuminate some of those interactions. In particular, one application is the pilot's interaction with the airplane via the feel system.

In the process of understanding the compatibility of the dynamics of the pilot and those of the airplane (via the various intervening elements), dynamic instability is the great enemy. Dynamic instability, when it involves airplane dynamics and a pilot is known as Pilot Induced Oscillation (PIO). Because of the insidious nature of the phenomenon and the potentially grave consequences of events, understanding the dynamic interaction between man and machine becomes even more important.

Consistent with Rasmussen's classifications, the FAA's recognition of how pilots operate the airplanes, and McRuer's understanding of human interaction with machine elements, pilots are seen as firmly rooted in the time domain. Regardless of engineers' passion for frequency-domain analysis (which is primarily a computational short-cut taken mostly for their own convenience), the pilot just does not see it that way. What the pilot sees is how the airplane responded in the first few seconds after the pilot made a control input. It is this observation which forms the basis for the skills-based behaviour referred to by Rasmussen and identified by FAA as requiring training. It is also the basis for the "internal model" of the airplane dynamics necessary for the pilot to be able to move between and make effective use of McRuer's pilot strategies.

1.6 Aims and Objectives of this work

The characteristics of large jet transports, their constituent parts, and how they are modelled for analysis and design will be seen to have an effect on the interaction with the pilot: the airplane handling qualities. The aim of this work is a better understanding of the critical interactions between pilots and large transport aircraft. This will be achieved through the following objectives:

1. Develop and articulate an understanding of the realities of large aircraft dynamic response and the implications for pilot closed-loop control, including low frequency modal dynamics, transient response to controls, and the consequent dynamics of relaxed static stability.
2. Consider the implications of specific model element forms and make recommendations for their use in Handling Qualities analysis for large transport aircraft including the quasi-steady aerodynamic assumption and the order of actuator models used in simulation.
3. Assess the effects of linearity in the cockpit feel system, develop a method for establishing boundaries on force/displacement relationships in terms of handling qualities, and develop a set of boundaries for lateral control with a wheel.

4. Use pilot modelling techniques and the results achieved with them to develop understanding of the interaction of pilots with the feel characteristics of large aircraft.
5. Develop and assess a PIO propensity prediction criterion.

1.7 Organization of the Thesis

Chapter 1 sets the stage for the thesis by providing a brief introductory discussion of the high level topics relevant to large airplanes being controlled by human pilots. Within the context of this introduction, the aims and objectives of the research are set out and the organization of the thesis report is described.

Chapter 2 sets out the historical context of the relationships between flight dynamics and handling qualities. This serves at least two purposes. First, it provides background and context to understand where the challenges originated, and second, it points out from the historical record that many challenges are not quickly resolved.

The literature survey in Chapter 3 serves to establish the state of the art with regard to the elements identified for study, and points out the relevance of each to the larger subject of handling qualities in the context of large transport aircraft. This will identify deficiencies in the state of the art and set the stage for the research and results to follow in Chapter 4.

Chapter 4 presents the research and results related to each topic enumerated in Chapter 3.

Chapter 5 collects and summarizes the important findings of the research and illustrates the importance of considering the airplane and its elements as a whole from the point of view of the pilot who is trying to close a control loop through all of those interacting elements.

Conclusions are drawn in Chapter 6, answering the Aims and Objectives laid out in this chapter (Section 1.7).

Finally, as Chiardi suggests on page 1, there are always more questions than answers, and each answer seems to generate even more questions. Chapter 7 collects recommendations for further work arising from the findings here.

References are followed by Appendices, containing more details not included in the body of the text.

Figure 1-4 Newest Boeing and the Oldest Boeing

Boeing's 787 and Addison Pemberton's Boeing Model 40A meet just North of Mt. Rainier in Western Washington State.
The differences in technology are striking.
Photo courtesy of Boeing.

2 Historical Context

> The fact that an opinion has been widely held is no evidence whatever that it is not utterly absurd…
>
> Bertrand Russell[‡]

> True opinions can prevail only if the facts to which they refer are known; If they are not known, false ideas are just as effective as true ones, if not a little more effective.
>
> Walter Lippmann[§]

Understanding of the dynamics of flight grew up in the United Kingdom. Nearly 100 years after Cayley's experiments in the 19th century, Lanchester began tossing gliders from his bedroom window in Warwick and studying the dynamics of the motion (Burnett, 1979). By systematically varying the surface proportions and weight distribution and studying the effects on the dynamic motion, Lanchester came to the conclusion that it was possible to achieve natural stability, observing the stability of the long-period mode, which he named "phugoid". Similarly, Penaud in France was experimenting with models, though his were rubber powered. His planophore introduced both dihedral (which Cayley had worked out almost 100 years earlier, but was unknown to Penaud) and setting the tailplane at a smaller angle of incidence than the wing, thus affording automatic, or natural stability (Gibb-Smith, 2003).

Penaud's and Lanchester's experiments were on unoccupied gliders, which were quite small (i.e. of small inertia) and their analysis was focused on dynamics of the vehicle with fixed controls. As soon as men tried to fly along, the focus widened considerably to include the element of control: men wanted to be able to control the flight path of their new-found vehicles.

In the late 1800's, Lilienthal in Germany successfully demonstrated that a glider could carry a human. For the first time, with man on board, there arose a *need* for control. These first experiments were on vehicles incorporating stability, or the natural tendency to recover from an upset, and for the first time incorporated a means of control by means of the pilot shifting the location of his body: weight shift.

[‡] Bertrand Russell was a British author, mathematician, philosopher, and logician, who was awarded the Nobel Prize for Literature. (Russell, 1929)

[§] Walter Lippmann was an American journalist, a two-time Pulitzer Award winner, and the origin of the term "cold war". (Lippmann, 1920)

Control by weight shift of the pilot necessarily limited the size of the glider (Cook, 1994, Cook, 2006, Schmidt, 2012).

The Wright brothers in America took a different approach. Their concern with this conundrum of balance and the ability to control the vehicle was expressed by Wilbur in his address to the Western Society of Engineers in 1901 (Perkins, 1970), two years before their first powered flight:

> "The ability to balance and steer still confronts students of the flying problem. When this one feature has been worked out, the age of flying machines will have arrived, for all other difficulties are of minor importance."

They dispensed with natural stability, deliberately in the roll axis, deciding instead to afford themselves sufficient control (they spent years teaching themselves to fly their unpowered gliders). Culick (2001), who has studied the Wright's works has concluded that they simply did not understand longitudinal stability.

Laterally, the Wright brothers abandoned the notion of natural stability, as was adopted by the Europeans in favour of controllability. They had decided that stable airplanes responded too readily to turbulence (McLean, 1990)/

After the Wright brothers demonstrated their machine and its considerable control power in France in 1908, the European community very quickly adopted the notion of mechanical controls, although the methods of mechanizing the link between the pilot and the controls was still a subject of widely diverse experimentation. Abzug and Larabee give some insight (1997). The Wrights, once they abandoned the hip-cradle and the prone-position for the pilot, adopted independent levers for roll/yaw and for pitch. Breguet used a wheel/stick arrangement in which the fore-and-aft motion controlled pitch, lateral motion of the stick controlled roll, and rotation of the wheel controlled yaw. The common centre-stick arrangement used by many including early Farman airplanes was patented by Robert Ensault-Pelterie and referred to as the R.E.P. control. Parks (2009) points out that the now-common arrangement of controlling elevators (pitch) with a fore-aft moving column, controlling lateral motion (roll) with a wheel attached to the top of the pitch stick, and controlling the rudder (yaw) with pedals originated from the company *Société de Production des Aéroplanes Deperdussin* (commonly referred to as SPAD). The arrangement is attributed to Louis Béchereau, the talented designer employed by Deperdussin, who was not a designer himself. Béchereau's implementation is illustrated in Figure 2-1 taken from Parks, (2009). (It is interesting to note that Deperdussin referred to the lateral control as "balancing control".)

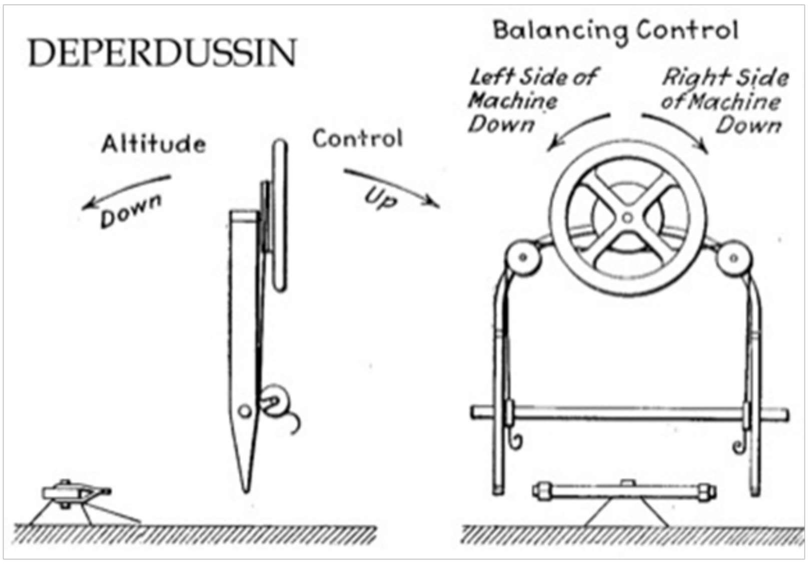

Figure 2-1. Deperdussin Control
(Parks, 2009)

By the 1930's, the wheel atop the pitch stick instead of the lateral stick for roll control had become common. It is seen that this arrangement is functionally identical to that used in a modern jet transport aircraft, illustrated in Figure 2-2. In the late 1980's after building a series of transports with "traditional" Deperdussin controllers, Airbus Industrie introduced a small sidestick controller in their fly-by-wire aircraft, illustrated in Figure 2-3. Advantages of this particular arrangement (which is really an R.E.P. stick controller, only smaller and offset to the outside of each pilot station) lie in areas other than pilot control (freeing up space for a meal tray, etc.). Finally, there are large transport aircraft with large-displacement R.E.P. stick controllers, one of which is illustrated in Figure 2-4.This serves to illustrate the fact that after nearly a hundred years' further development, there appears to be no "one right way" to implement the control functions. The devil is, of course, in the details.

Figure 2-2. Boeing 787 Flight Deck with Traditional Deperdussin Controllers. Photo courtesy of EAA.

Figure 2-3. Airbus A380 Flight Deck with Small-Displacement Sidesticks. Photo courtesy of EAA.

Figure 2-4. Boeing C-17 Flight Deck withArticulated R.E.P Centre-Stick Controllers.

Photo courtesy of Boeing.

As soon as man became a controller of the airplane, the need to understand how best to disposition the arrangement of surfaces – and later, to augment the stability and control characteristics – to best suit the pilot's ability to manoeuvre the airplane in the presence of atmospheric disturbances became apparent. This recognition, *that it is the pilot's ability to interact with the airplane to make it manoeuvre at his will*, took quite a long time to develop. Vincenti points out that at the end of WWI, it was not at all clear that pilots wanted airplanes which were stable, but by the late 1930's the focus on what the pilot needed had made the situation more clear (Vincenti, 1990). While in the 1910's, there were theoreticians who understood the notions of stability and control, those who were designing, building and flying airplanes did not, and the two groups did not talk to each other (Vincenti, 1988). Vincenti goes on to describe that the primary influence of the theory was to inspire wind tunnel testing, both at MIT and at the National Physical Laboratory in the UK. While these tests revealed the levels of stability (or not), there was still no way to know just what the pilots needed. Vincenti quotes Eddie Allen and Fredrick Norton of NACA in 1921 saying “Generally speaking, a pilot does not know a stable from an unstable machine, and if the forces on the controls are small, he is just as well satisfied with the unstable one as the other...” (Vincenti, 1988), but goes on to quote Kelly Johnson in 1935 in an article on the Lockheed Electra as saying “The reasons why an airplane must be stable are more or less obvious...”. At least one of those reasons had to do with flight times and pilot fatigue.

The next breakthrough came in the 1939 realization of the importance of the Short Period mode by Gough and Gilruth (Vincenti, 1990). Three years earlier, Hartley Soulè could not find much correlation between pilot opinion and the phugoid motion (Soulè, 1936). Vincenti (1990) reports that it was a chance disturbance on a takeoff in a Lockheed Super Electra (L-14H) which generated a short period oscillation which alerted Gough to the presence of and potential interference from the short period of motion.   Gilruth decided that the mode should be heavily damped.   Even though Gilruth’s regulation of damping of this mode was done on the basis of objectionable interference with the pilot’s task (not on the basis of favourable “tuning” for dynamic performance), this represented the first step in the reversal of the importance of the phugoid and the short period natural modes. Of course, airplanes were getting bigger, heavier, considerably faster, and endured significantly longer flight times.

In the 30 or so years to follow, significant work would progress in identifying short period characteristics which were “favourable”. These appeared first in the form of the famous thumbprint specification. One example of this work can be found in Newell and Campbell (1954), in which they set out to determine optimum and minimum flyable conditions in the variable-stability B-26. Results are plotted as short period frequency vs short period damping. Roskam (1979b) has pointed out that these results generated some considerable debate as they predicted large jet transports would have poor handling, contrary to experience at the time. This discrepancy is illustrated in Figure 2-5. Stengle (2004) points out that the specification of frequency and damping alone is not sufficient for the specification of longitudinal handling because those parameters do not identify the response to controls. Response to control inputs requires the numerator terms of the respective transfer functions. The discrepancy identified in Figure 2-5 and the associated debate led Shomber and Gertsen (1967), to investigate the importance of parameters n_{z_α}, L_ε/ω_n, and n_z/ω_n, in bringing consistency to measured ground- and in-flight simulation results. Gibson (1999) reports that he found that the addition of the numerator terms was particularly well suited for the consideration of his ideas at the time (although there remained some debate about boundary locations). By 1987, the additional consideration of these terms had become recognized and was incorporated in the first version of MIL-STD-1797.

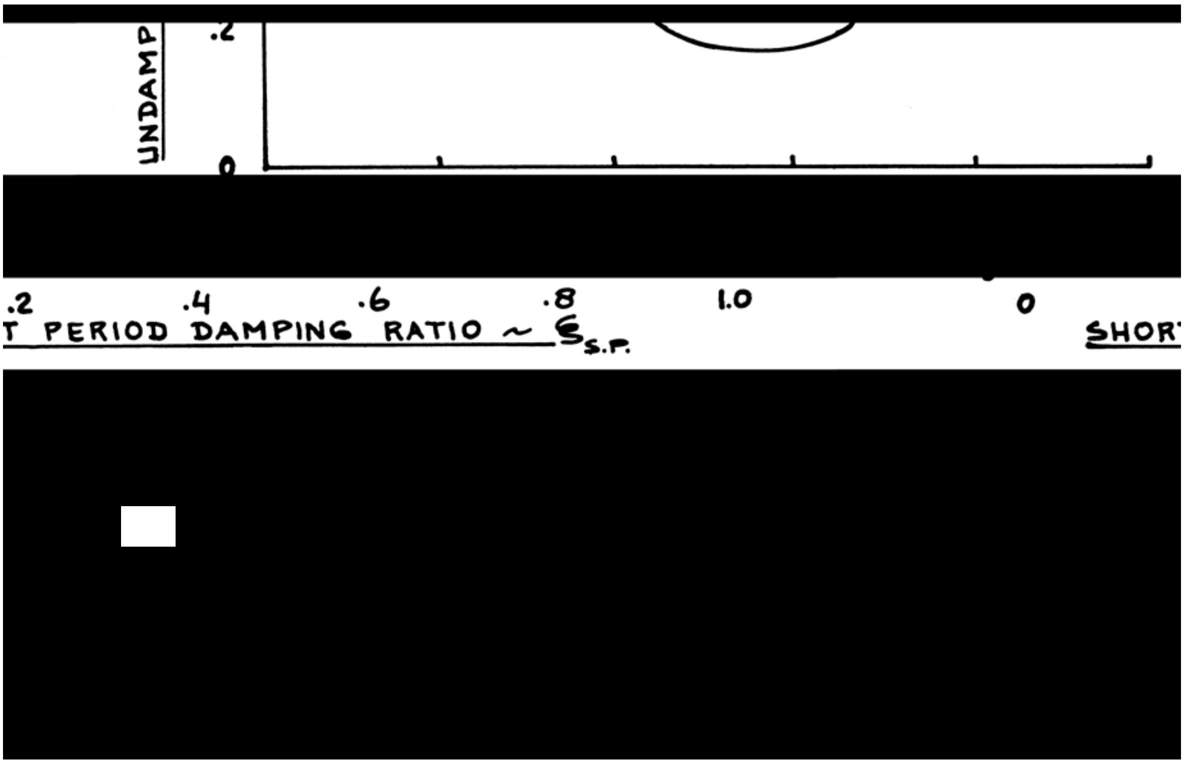

Figure 2-5. Early "Thumbprint" Criteria and Predicted Jet Transport Characteristics.
From Roskam (1979b)

From the first recognition of the short period as significant to handling, and its relegation to "heavily damped" to keep it out of the way of the pilot to a specification of boundaries which included both the natural stability mode and the response to control numerator terms took nearly 50 years of research

The art of airplane handling qualities is all about matching the airplane dynamics to those of the human pilot: to ensure that the result of their collaborations are harmonious, that is, the pilot can command his will over the flight path of the airplane in a satisfactory way, and at the same time that the risk of the resulting collaboration being unsatisfactory (e.g. unstable), is acceptably small. This thesis extends the state of the art to examine the critical relationships between the human pilot and the airplane – in particular for large transport airplanes.

While there has been recognition of the fact that airplanes of different sizes might represent a need for different requirements, the development of those has progressed rather heuristically…that is without detailed study of the characteristics as airplane size changes. This is particularly true for the case in which the human is the primary controller. There is evidence that these processes need to continue to evolve.

Figure 2-6 Boeing 747 Large Cargo Freighter (LCF) Touches Down at Everett, WA.

This heavily modified 747 is designed to carry 787 components from manufacturing facilities around the world to Everett for assembly. The aft fuselage swings open for access to the cargo bay. Note the external hinge fairing just forward of the vertical fin. Systems routings are through the hinge fairings.
Photo courtesy of J.C.E.Lee

3 Establishing the State of the Art

If I have seen farther, it is by standing the shoulders of giants.

Sir Isaac Newton*

Many times a day I realize how much my outer and inner life is built upon the labours of my fellow men, living and dead, and how earnestly I must exert myself in order to give in return as much as I received. My peace of mind is often troubled by the depressing sense that I have borrowed too heavily from the work of other men.

Albert Einstein†

The traditional literature review in every serious academic work serves a number of important roles. First, it demonstrates a recognition that serious work has been done by other researchers previously. This previous work provides a foundation and a jumping-off point for the current work. Documenting this work demonstrates knowledge, if not mastery of the various topics involved.

Second, there is an element of demarcation illustrated: the identification of what was done previously, and the current work.

Finally, the organization of this previous work should indicate and provide background for the original work to come.

In this case, the subject of airplane handling qualities for large transport aircraft involves a number of sub-disciplines. Obviously, the airplane dynamics, including all of the systems between the pilot and the airplane motion are involved. Then there is the pilot himself, taken as a system, or elements of a system. Together, these form the basis for analyses of their complex interactions ranging from stable trajectory-following command to instability manifested by Pilot Induced Oscillations (PIO). This analysis is the study of airplane handling qualities.

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* Part of a letter Newton wrote to Robert Hooke, 5 February, 1675-6 (Newton, 1675-6)
† Einstein writing about his personal philosophies, (Einstein, 1930)

3.1 Flight Dynamics of Large Transport Aircraft

3.1.1 Equations of Motion

As noted in Chapter 2, the foundations for understanding the dynamics of airplanes began with Lanchester, and while human-carrying powered flight was still in its infancy, Bryan (1911) had essentially laid out the basis for analytic understanding.

Development of the equations typically involves a number of assumptions. For each particular application, the assumptions made in the development of the describing equations are really important. McRuer, Ashkenas, and Graham (1973) spell them out quite explicitly as:

1. The airplane acts as a rigid body.
2. The earth is fixed in space.
3. The airplane mass and mass distributions are constant.
4. The X-Z plane is a plane of symmetry.
5. The perturbations from steady flight conditions are small.
6. The steady lateral trim conditions are: $p_0 = r_0 = v_0 = \phi_0 = 0$ and longitudinal forces and moments due to lateral perturbations are negligible.
7. The flow is quasi-steady.
8. Variations in atmospheric properties are negligible for the perturbations of interest.
9. Rotations of the vertical are negligible; trimmed pitch rate is zero; implies straight flight over a flat earth.
10. $X_{\dot{w}} = X_q = Z_{\dot{w}} = Z_q = 0$.
11. The steady flight path is assumed to be horizontal $\gamma_0 = 0$.

Nevertheless, the equations of motion are well known, reproduced by any number of authors, and are not particularly controversial.

Linearization about an equilibrium point provides, as explained by McRuer, Ashkenas, and Graham (1973) the possibility to use the convenient transfer function models for the dynamics of the vehicle and “all the analytical techniques for the study of linear feedback systems can be brought to bear on the problem.”

The linearized, small-perturbation equations describing de-coupled longitudinal motion can be written (using US dimensional derivatives, after Roskam (1979a), but ignoring thrust forces and moments) as:

$$\dot{u} = g\theta\cos\theta_1 + X_u u + X_\alpha \alpha + X_{\delta_e}\delta_e$$

$$\dot{w} - U_1 q = -g\theta\sin\theta_1 + Z_u u + Z_\alpha \alpha + Z_{\dot{\alpha}}\dot{\alpha} + Z_q q + Z_{\delta_e}\delta_e \qquad (3.1)$$

$$\dot{q} = M_u u + M_\alpha \alpha + M\ \dot{\alpha} + M_q q + M_{\delta_e}\delta_e$$

And after taking Laplace transforms:

$$(s - X_u)u(s) - X_\alpha \alpha(s) + g\cos\theta_1\theta(s) = X_{\delta_e}\delta_e(s)$$

$$-Z_u u(s) + \{s(U_1 - Z_{\dot{\alpha}}) - Z_\alpha\}\alpha(s) + \{-(Z_q + U_1)s + g\sin\theta_1\}\theta(s) = Z_{\delta_e}\delta_e(s) \qquad (3.2)$$

$$-M_u u(s) - \{M_{\dot{\alpha}}s + M_\alpha\}\alpha(s) + (s^2 - M_q s)\theta(s) = M_{\delta_e}\delta_e$$

Equations 3.2 in Matrix format becomes:

$$\begin{bmatrix} (s - X_u) & -X_\alpha & g\cos\theta_1 \\ -Z_u & [s(U_1 - Z_{\dot{\alpha}}) - Z_\alpha] & [(-Z_q + U_1)s + g\sin\theta_1] \\ -M_u & -(M_{\dot{\alpha}}s + M_\alpha) & (s^2 - M_q s) \end{bmatrix} \begin{Bmatrix} \dfrac{u(s)}{\delta_e(s)} \\ \dfrac{\alpha(s)}{\delta_e(s)} \\ \dfrac{\theta(s)}{\delta_e(s)} \end{Bmatrix} = \begin{Bmatrix} X_{\delta_e} \\ Z_{\delta_e} \\ M_{\delta_e} \end{Bmatrix} \qquad (3.3)$$

Schmidt, (2012) refers to this form as a “polynomial-matrix description” (PMD), and notes that this is a preferred form because it gives physical visibility to the constituents of the equations, and because it allows use of Cramer’s rule to form the transfer functions, which can be done by hand because it does not involve a matrix inversion.

Alternatively, and equivalently, these relationships can be expressed in the state-space form, using the helpfully compact “concise” derivatives with the state space equation given by (after Cook, 2007):

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} x_u & x_w & x_q & x_\theta \\ z_u & z_w & z_q & z_\theta \\ m_u & m_w & m_q & m_\theta \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} x_\eta \\ z_\eta \\ m_\eta \\ 0 \end{bmatrix} \eta \tag{3.4}$$

Both the PMD representation and the State Space representation provide a coupled set of linear differential equations which describe the simultaneous motion in 4 states (the perturbation in forward speed u, the perturbation in vertical speed w, the perturbation in pitch rate q and the perturbation in pitch attitude θ) as a function of the control deflection, in this case elevator deflection, given by δ_e in the US convention and η in the British convention (although the PMD as given lacks the pitch attitude – pitch rate relation). These describe a Single-Input-Multiple-Output (SIMO) system. Either form provides ready access to the system characteristic equation, which describes the stability properties of the system.

The solution of the characteristic equation will reveal that it has 4 roots; each root represents a “characteristic mode” of motion in the solution. Depending on the values of the variables which represent the configuration and the flight condition, those 4 roots might exist in several combinations: they may exist as 2 sets of complex conjugates, one set of conjugates and 2 independent real roots, or 4 real roots.

Because each root (or pair of roots) represents a constituent of the whole motion which has a particular character, it is often illustrative to solve the set of equations in terms of these characteristic modes of motion. Cook (2007) points out:

> “This is a very useful facility for investigating the response properties of an airplane especially when the behaviour is not conventional, when stability modes are obscured or when a significant degree of mode coupling is present.” (p. 124)

It is possible to compute the time-domain solution in terms of the mode shapes, that is in terms of the eigenvectors and eigenvalues, of the form given in Figure 3-1. Often, though, actually computing the time solution in this way is not necessary in order to evaluate the mode shapes. Simply evaluating the eigenvectors and eigenvalues is sufficient. All of this is available in most popular texts, e.g. Roskam (1979a), Cook (2007).

What the solution in this form provides is important visibility into just how the resulting motion originates; how it is formed. Each eigenvalue (or pair, if they are conjugates) represents a motion at a unique frequency and damping. As seen in Figure 3.1, for a Multi-Input-Multi-Output system, the motion represented by each eigenvalue (or pair) is multiplied by a unique combination of eigenvectors. The eigenvectors provide visibility of the motion of each state, both magnitude and phase, relative to each other state.

For example, if Figure 3-1 represented a classical longitudinal solution of aircraft dynamics and modes 1 and 2 were conjugates representing the phugoid motion, the phugoid would be described as a mode which oscillated at a particular frequency and exhibited a particular damping. But the motion of each of the 4 states would vary (at the phugoid's frequency and damping) according to the eigenvector associated with that motion. That is, each of the states, say, speed, angle of attack, pitch rate, and pitch attitude, would each vary at the frequency of the phugoid, the amplitudes of their motion would be as described by the damping of the phugoid, but the *relative* amplitudes and *relative* phases between the 4 states would be as described by the eigenvector associated with the phugoid. And the same is true for the short period motion.

The total motion in each state is the sum of the contributions from each mode.

$$\Delta\vec{x}(t) = \rho_{c_1} e^{i\phi_{c1}} e^{(\sigma_1 + i\omega_1)t} \begin{bmatrix} \rho_{v_{11}} e^{i\phi_{v\,11}} \\ \rho_{v_{21}} e^{i\phi_{v\,21}} \\ \rho_{v_{31}} e^{i\phi_{v\,31}} \\ \rho_{v_{41}} e^{i\phi_{v\,41}} \end{bmatrix} + \rho_{c_1} e^{-i\phi_{c1}} e^{(\sigma_1 - i\omega_1)t} \begin{bmatrix} \rho_{v_{11}} e^{-i\phi_{v\,11}} \\ \rho_{v_{21}} e^{-i\phi_{v\,21}} \\ \rho_{v_{31}} e^{-i\phi_{v\,31}} \\ \rho_{v_{41}} e^{-i\phi_{v\,41}} \end{bmatrix} + \rho_{c_3} e^{i\phi_{c3}} e^{(\sigma_3 + i\omega_3)t} \begin{bmatrix} \rho_{v_{13}} e^{i\phi_{v\,13}} \\ \rho_{v_{23}} e^{i\phi_{v\,23}} \\ \rho_{v_{33}} e^{i\phi_{v\,33}} \\ \rho_{v_{43}} e^{i\phi_{v\,43}} \end{bmatrix} + \rho_{c_3} e^{-i\phi_{c3}} e^{(\sigma_3 - i\omega_3)t} \begin{bmatrix} \rho_{v_{13}} e^{-i\phi_{v\,13}} \\ \rho_{v_{23}} e^{-i\phi_{v\,23}} \\ \rho_{v_{33}} e^{-i\phi_{v\,33}} \\ \rho_{v_{43}} e^{-i\phi_{v\,43}} \end{bmatrix} \begin{matrix} \leftarrow u \\ \leftarrow w \\ \leftarrow q \\ \leftarrow \theta \end{matrix}$$

Mode 1 from Root 1 | Mode 2 from Root 2 | Mode 3 from Root 3 | Mode 4 from Root 4

The character of the motion contribution from each mode is defined by the eigenvalues: stable or unstable, oscillatory or aperiodic, slow or fast.

The shape of the motion of each mode: the contribution (magnitude) from each state and the phase of each state's contribution to the total motion is defined by the eigenvectors.

Figure 3-1. Time-Domain Solution Form in terms of Modal Characteristics

3.1.2 Reduced Order Forms

It has long been recognized that under the right conditions, for specific analysis purposes, certain assumptions may be imposed which allow the truncation of the equations of motion: longitudinal and lateral-directional sets respectively, into so-called “reduced order” approximations. When this works, it produces a solution for dynamic motion which is more tractable analytically, and more quickly grasped cognitively. This is most often done by truncation, and like the descriptions above, is done in most popular texts.

As an example, Cook (2007) demonstrates that starting with Equation (3.4), and applying knowledge that the short period mode is almost exclusively involving pitch rate q and angle of attack α with the speed remaining nearly constant, the perturbation speed equation and all speed-dependent terms may be removed, leaving:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} z_w & z_q & z_\theta \\ m_w & m_q & m_\theta \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} z_\eta \\ m_\eta \\ 0 \end{bmatrix} \eta \qquad (3.5)$$

By assuming the equations may be referenced to wind axes, it can be shown that these will become

$$\begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} z_w & z_q \\ m_w & m_q \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \begin{bmatrix} z_\eta \\ m_\eta \end{bmatrix} \eta \qquad (3.6)$$

Considering “typical” relationships between aerodynamic terms, the two short-term transfer functions describing response to elevator may be formed and the characteristic equation generated

$$\Delta(s) = s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}{}^2 = s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e) = 0 \qquad (3.7)$$

By equating coefficients, it can be shown that the frequency and damping of the short period may be approximated by:

$$2\zeta_{sp}\omega_{sp} = -\left(\frac{\overset{o}{M}_q}{I_y} + \frac{\overset{o}{Z}_W}{m} + \frac{\overset{o}{M}_{\dot{W}} U_e}{I_y} \right) \text{ and } \omega_{sp} = \sqrt{\frac{\overset{o}{M}_q}{I_y} \frac{\overset{o}{Z}_W}{m} \frac{-\overset{o}{M}_w U_e}{I_y}} \tag{3.8}$$

Similarly, the phugoid may be isolated by noting that its motion is dominated by speed and pitch attitude perturbations, so it is possible to set $\dot{w} = \dot{q} = 0$ it may be shown that the phugoid may be approximated by

$$\zeta_p \cong \frac{1}{\sqrt{2}} \frac{C_D}{C_L} \text{ and } \omega_p = \frac{g\sqrt{2}}{V_0}. \tag{3.9}$$

Similar approximations exist for the lateral-directional modes, but most texts warn against generalization; they are not as reliable as those in the longitudinal axis. Therefore, it's usually advisable to use the full 3-degree-of-freedom solutions for the lateral-directional parameters.

3.1.3 The Ubiquitous Second Order Problem

Many authors have pointed out that the solution to a second order differential equation is quite useful in the study of dynamics, and this is certainly true in the study of flight dynamics. Therefore, it is useful to spend some effort to understand just what that equation and its solution means. This material is summarized in Appendix A.

3.2 Flight Dynamics Requirements

3.2.1 Philosophy for Requirements on Dynamics of Large Aircraft

The philosophical approach to specifying static and dynamic characteristics are different between civilian and military authorities, and this difference shows up in the respective requirements. On the civilian side, the FAA's philosophical position is found in paragraph 25.21 which states in part that compliance with the various requirements shall be shown by tests on the airplane or by calculations based on and equal in accuracy to the results of testing. So while compliance via analysis is allowed, the burden of proof of accuracy is so great that it is rarely invoked (except in cases in which actual testing on the airplane is considered too dangerous or not practical). The military on the other hand, specifies characteristics in significantly more detail and expects compliance to be shown via computations using mathematical models. There is validation testing in military procurement programs, to be sure, but the point here is that there is greater reliance on the results of analysis.

Even though those philosophies are different, there are similarities. It turns out that a unifying element is the subjective evaluation. Airplane handling qualities have always been quite subjective, that is, their evaluation and declaration of suitability have always been subject to the interpretation of the evaluating pilot. The challenge this poses was recognized in the second decade of flight by a Captain Student, speaking during a meeting in Germany in 1918, the proceedings of which were translated by NACA in 1923 (Student, 1923).

> "Manufacturer's pilots become somewhat biased through numerous flights with airplanes of the same type, and are, in most cases, therefore, hardly in a position to determine accurately the real flying qualities of new types." (p. 185)

It was seen in Chapter 2 that this took a long time for the industry to sort out. Because of the subjective nature of the evaluations, standardization of the evaluation itself is also a significant issue to be addressed, as, even within one company, different pilots may have different opinions about particular situations.

This need for standardization is being addressed in a number of ways, albeit on a time scale similar to that related in Chapter 2. One major breakthrough in this area was the landmark paper by Cooper and Harper (1969a, 1969b). The focus of the paper is on *communication* between evaluating pilots and engineers. To facilitate that communication, Cooper and Harper advocate a standardized language, used in the context of specific manoeuvre evaluations using a very specific process. One element of that process is use of their rating scale, which has become universal . The rating scale is shown in Figure 3-2.

The fact that the rating scale is universally known and even used, however, does not necessarily mean that the process by which it is to be used is universally practiced. The need for these processes was reinforced 15 years after their original paper in Cooper and Harper's Wright Brothers Lecture (Cooper and Harper, 1984).

Six years later, Roger Hoh gathered a number of lessons learned about the need to pay attention to these processes and admonished the industry to do just that (Hoh, 1990). Six years after that, Hoh and Mitchell (1996) stressed again the need for disciplined processes in evaluating airplane handling qualities in the context of flight control system design.

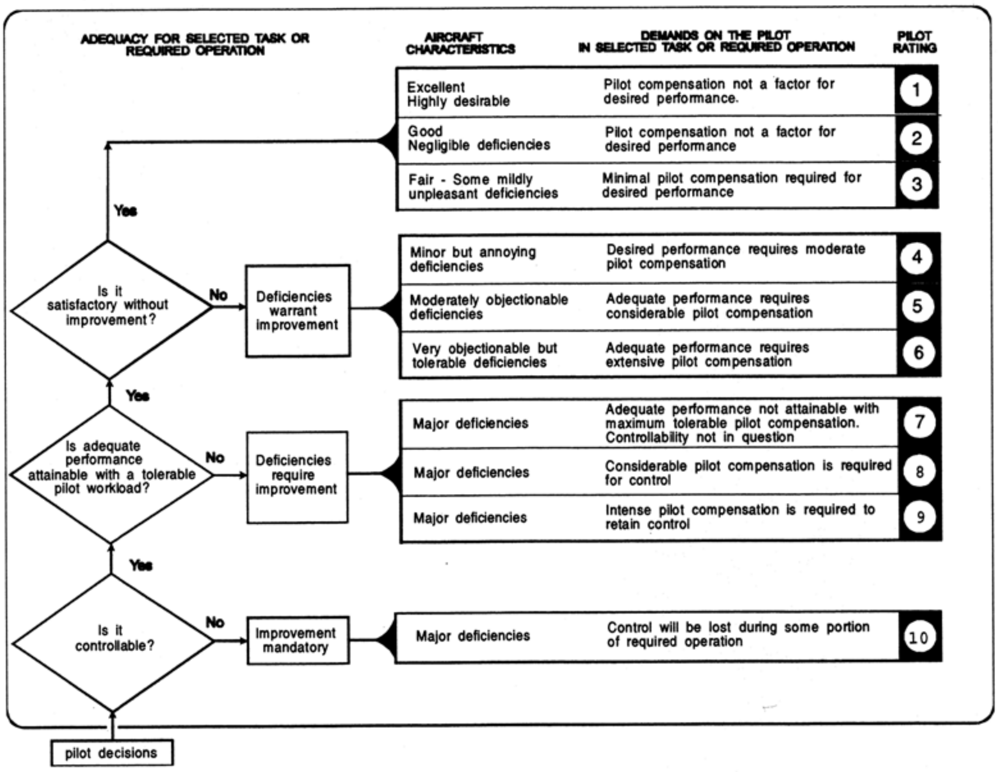

Figure 3-2. Cooper-Harper Handling Qualities Rating Scale

On the civilian side, the regulating authorities are interested only in enforcing a minimum level of safety. That is to say, there is no guidance regarding "optimum" handling qualities; the requirements only specify those characteristics which are "just acceptable". These are typically specified in terms of the subjective evaluations with descriptors such as “not requiring exceptional strength or skill”.

One major step in the process of generating predictable processes for civilian certification evaluations has come with the introduction of the FAA’s Handling Qualities Rating Method (HQRM). This was invented initially as a way to conduct evaluations of advanced fly-by-wire transport aircraft which did not necessarily meet the specifications of 14CFR25[*] (for example, Part 25 requires stick force stability with respect to speed, and the Airbus family of fly-by-wire transport aircraft do not have this feature, yet they have nevertheless been found to be safe). The method has since been applied to evaluation of failure conditions, and has been codified as an acceptable means of compliance in the advisory circular 25.7C, Appendix 5. (FAA, 2012).

It should be pointed out that in Europe, the European Aviation Safety Agency[†] (EASA) has not adopted HQRM as a matter of standards harmonization. This has been discussed at great length in the harmonization activities over the past 15 years or so, and the EASA (nee JAA) representatives prefer to defer to the subjective evaluations of their test pilots.

Both the military flying qualities requirements and the civilian evaluation criteria in HQRM speak in terms of handling qualities “levels” for specific aircraft classes, specific flight phases, specific flight envelopes, and increasingly, for specific mission task elements. These levels are parallel on both the military and civilian sides, and can be thought of as being held together by the evaluation processes: Cooper-Harper and HQRM. The understanding of these

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[*] What used to be commonly referred to as “FAR Part 25” is now called 14CFR25, because these certification requirements for Transport Category Aircraft (above 12,500 lbs.) are contained in Part 25 of Title 14 of the US Code of Federal Regulations. The common acronym “FAR” which formerly had the colloquial meaning “Federal Aviation Regulation” has now been formally allocated to the “Federal Acquisition Regulations”, evidently much more widely used by government employees than the Federal Aviation Regulations. Even though the term FAR was seen to cause confusion outside the aviation industry, old habits die hard, and most industry insiders still refer to the transport aircraft certification regulations as “FAR 25”. The Federal Aviation Administration maintains a historical record of regulation changes on its “regulatory and guidance library” web site: http://www.rgl.faa.gov.

[†] With the creation of EASA in Europe (to replace the former Joint Aviation Authorities, (JAA), the former Joint Aviation Regulations (JAR 25) has now been replaced by a “Certification Standard 25”, or CS25.

levels and just what they mean is so important that it is worth a detailed review. Details are discussed in Appendix B.

In the civilian certification world, FAA's Handling Qualities Rating Method (HQRM) mirrors this philosophy and in fact, provides a direct read-across to the military handling qualities levels. One minor difference exists in that HQRM does not allow Cooper-Harper ratings of 9 to be considered "controllable". What is more important is that neither set of standards suggests that Level 3 ratings would allow continued *safe* flight and landing. FAA's HQRM is shown in Table 3.1.

FAA HQ Rating	FAA Definition	Cooper-Harper	MIL Level	MIL Qual
Satisfactory	Full performance criteria met with routine pilot effort and attention	1-3.5	1	SAT
Adequate	Adequate for continued safe flight and landing: full or specified reduced performance met, but with heightened pilot effort and attention	3.5-6.5	2	Accept
Controllable	Inadequate for continued safe flight and landing, but controllable for return to safe flight condition a safe flight envelope, and/or reconfiguration so that HQ are at least ADEQUATE	6.5-8	3	Con

Table 3-1 FAA HQRM Rating Scale Definitions
(After FAA, 2012)

FAA's finding of "controllable" only suggests that the pilot can retain control long enough to reach a "retreat envelope" or reconfigure the airplane in such a way that the characteristics become "adequate", and the flight can be continued, and landed, safely.

3.2.2 Civilian Requirements on Dynamics of Large Transport Airplanes

For civilian certification, the requirements only specify that short period oscillations be "heavily damped" Further, the guidance material in AC25-7C (FAA, 2012) specifies that "heavily damped" means damped to 1/10 amplitude in 2 cycles. That works out to a damping ratio, ζ, of 0.18. Of course, a positive damping ratio implies that the short period must be stable. Civil authorities do not specify bounds on short period frequencies.

Similarly, phugoid characteristics are not addressed in civilian requirements, except via the general stability requirement which specifies that stability should be "suitable". A more detailed comparison of civilian and military requirements on dynamics is given in Appendix C.

3.2.3 Military Requirements on Dynamics of Large Transport Aircraft

In contrast to, and because of the philosophical differences from the civilian requirements, the military requirements (US Department of Defense, 1997[‡]) on dynamics are much more detailed in terms of techniques to be applied as functions of control system architecture and in terms of depth of the detail. This may also stem from the different mission focus that the military has. The military requirements nearly always include different parameter values or boundaries for different airplane classes, presumably under the assumption that airplanes of different classes need to perform different missions. While there has been and remains different sets of requirements for different airplane

[‡] The long-standing and venerable MIL-F-8785 series of documents were replaced by MIL-STD-1797 in 1987. This was revised to MIL-STD-1797A in 1990. In 1997, the US-Department of Defense changed the designation of this material from a "standard", that is, a contractual requirement for procurement activities to a "handbook", useful for guidance but not to be used as a contractual standard, and thus MIL-HDBK-1797 was born. The only change at that time was to the cover page. Regardless of its status relative to contractual matters in government procurement, this document, along with its appendix, (as well as its predecessors and their respective Background Information and User Guides (BIUGs)) represents the central repository of what is known about flying and handling qualities of piloted airplanes. The contents are well vetted and represent decades of lessons learned. For a more complete discussion of the history of flying qualities requirements in the US, see Cotting (2010).

“classes” (usually weight classes, but also consideration for the intended mission), there is a trend in the past few years towards mission-oriented requirements, in which the size of the airplane does not matter. What matters is whether the airplane can perform the mission and its tasks. Following the example set by the rotorcraft specification, ADS-33 (Aeronautical Design Standard, 2000), there has been work to move the fixed-wing specifications in that direction (Mitchell, Hoh, and Aponso, 1994). Nevertheless, the pilot must still make the evaluation, and it was noted by Weingarten and Chalk (1981) that even thought the task in that study was the same (precision landing) as in previous studies conducted at Calspan, the evaluation pilots used noticeably less aggressiveness in performance of the task because “the configurations were defined to be very large, one-million pound, Class III aircraft”. It is also possible that these pilots’ level of aggressiveness was tempered by a priori knowledge that very aggressive handling of flight controls on large airplanes frequently excites low-frequency structural modes which do not help to control the airplane, but only add to workload and frustration.

Regarding short period characteristics, the military requirements now refer to these as “short term pitch response”, as opposed to strictly discussing frequency and damping of the “short period”. This is in direct response to the discussions in the 1960’s regarding the importance of the numerator terms in the relevant transfer functions. The requirements are presented in several forms, catering to a wide array of response types, classical or not but still include limits on frequency and damping of the short period mode of motion. The preferred incarnation for short period characteristics is a combination of the CAP criterion, which includes the effects of the numerator terms, short period damping limits, and limits on equivalent time delay. To apply this criterion, to a high-order but still classically responding airplane, the airplane dynamics are represented by a Low Order Equivalent System fitting the whole airplane response to a 4^{th} order representation plus a time delay. The requirements are then imposed on the model thus obtained. A more detailed discussion is contained in Appendix C.

The military requirements impose a minimum short period damping of 0.35 for Level 1 and 0.25 for Level 2 for Category C (terminal area) operations. This is more stringent than FAA's 0.18. In addition to the CAP boundaries, the military requirements impose a minimum on short period frequency, for terminal operations for Class III (large) airplanes of 0.7 rad/sec. This as opposed to FAA not imposing any such limitation at all.

3.2.4 Summary of Requirements on Dynamics

While both civilian and military requirements on airplane dynamics differ in philosophy and implementation, they have the same goal: to ensure at least safe handling. The civilian requirements rely on piloted evaluation for handling qualities and specify only a small handful of minimum quantitative requirements on characteristics and control power. The military requirements include more detail in terms of quantitative measures and in terms of the depth of the description, providing levels of handling as opposed to simply a single minimum. For this reason, the military requirements are quite valuable to designers of even entirely civilian airplanes.

A unifying element in both the military and civilian approaches is the piloted evaluation. On the military side, the quantitative requirements are specified in terms of the same handling qualities levels as are generated by the piloted evaluation. The element tying this together is the Cooper-Harper rating scale and its associated processes. On the civilian side, the FAA's Handling Qualities Rating Method mirrors the notions of military evaluations with only minor differences.

Realizing this unifying element underscores the need to ensure that test pilots are thoroughly trained in making qualitative assessments.

Regardless of these unifying elements, the requirements are still quite sparse. While the military requirements suggest a minimum short period frequency, there is no mention of the nature of the motion or the proximity to other modes.

3.3 Effect of Airplane Size

3.3.1 Effect of Airplane Size on Natural Frequencies

The discussion about the short period and phugoid approximations provide interesting insight into how these modes should be expected to change as a function of airplane size and weight. Recall that

$$2\zeta_{sp}\omega_{sp} = \frac{-\overset{o}{M}_q}{I_y} \text{ and } \omega_{sp} = \sqrt{\frac{-\overset{o}{M}_w U_e}{I_y}} \tag{3.10}$$

$$\zeta_p \cong \frac{1}{\sqrt{2}}\frac{C_D}{C_L} \text{ and } \omega_p = \frac{g\sqrt{2}}{V_0} \tag{3.11}$$

The phugoid frequency is inversely proportional to airspeed, so as airplanes go faster, the phugoid frequency should get smaller. Phugoid damping is inversely proportional to Lift/Drag ratio, so as airplanes become more efficient, the phugoid damping should get worse (smaller damping ratio).

Airplanes are sized for an intended runway environment, and landing distance is a strong function of final approach speed. If larger airplanes of the future are expected to use the same runways that are in use today, we might expect the phugoid frequency to not change much from the airplanes of today, simply because in order to land in the same runway length, they will have similar approach speeds.

The short period is another story: the frequency of this mode is inversely proportional to inertia, so as airplanes get big, the short period frequency should be expected to decrease. It is also directly proportional to static stability. If the static margin decreases, the short period frequency should also decrease. The resulting natural frequencies for representative transport aircraft are given in Table 3-2, the data for which were extracted from Heffley and Jewell (1972). Short periods of 7-8 seconds are quite large compared to those of smaller aircraft.

In addition to the absolute value of short periods getting longer (slower frequencies), it should be noted that the very large airplane configurations studied by NASA during the 1980's (Grantham, Smith, Deal, and Neely, 1984) included unaugmented characteristics in which the short period and phugoid frequencies were within 6 percent of each other. Of course, in this study the airplane's characteristics were modified by augmentation. As will be seen, the nature of the augmentation is important as is the augmentation-failed state.

Configuration	Weight Lbs.	Short Period Frequency Seconds
Convair 880	126007.	7.68
Boeing 747-100	564032	8.14
Lockheed C-5A	580756.	7.26

Table 3-2. Typical Transport Short Period Natural Frequencies
(Heffley and Jewell (1972)

The period cited for the 747-100 is at 564000. Lbs. The current 747-8I has a maximum landing weight of greater than 760000. Lbs. (Boeing Commercial Airplanes, (2012)), so it would be expected that there are airplanes in the fleet today with even longer (slower) short periods.

Configurations studied in the 1980's and including those flown on the US Air Force Total In-Flight Simulation facility (TIFS) looked at configurations of one million pounds weight with short periods between 8 and 11.5 seconds (Weingarten and Chalk, (1981)). In addition, the configuration studied by Myers, et al (1982) only weighed 300000 Lbs, but had an augmented short period of 11.3 seconds.

3.3.2 Effect of Airplane Size on Human Pilot Behaviour

Rasmussen noted that pilots needed to experience training in order to develop an appropriate repertoire of skills-based behaviours and to know when to implement them. Figure 3-3 shows data collected during a tracking task on a large airplane. Note that while both the command and the airplane dynamic response are slowly undulating, the pilot is controlling it with pulses. Note in particular the time between about 25 seconds and 35 seconds. The command is nearly a straight line at approximately 2 deg/sec roll rate. The wheel is a rate command device, so all the pilot would need to do over those 10 seconds would be to hold a constant 2 deg/sec roll rate, which is a constant wheel position. What the pilot chose, however, is a series of 3 pulses returning to zero wheel except for a brief pulse in the opposite direction near 30 seconds. Similarly, when the command turns around at 30 seconds, the pilot follows it (with a delay), but again, instead of a constant wheel to track it, the pilot choose to pulse the wheel in at 36 seconds and return it to zero, followed by another pulse. Note also the pilot's wheel pulses tend to come in ~5 degree increments, most at ~10 degrees, some at ~5 degrees, and a couple at ~15 degrees. This author's experience in several decades of watching how pilots fly airplanes is that when a pilot reverts to pulse-modulation as a control strategy, the pilot is confused. There is something in the response dynamics that gives the pilot pause, so he reverts to a pulse and wait strategy.

Sutton (1990) and Veldhuysen (1976) both report observing and modelling human operators of large vessels as pulse-wave generators. Veldhuysen cites earlier work of Stuurman (1969) reporting that in the case of ships a more-or-less bang-bang control strategy was applied by subjects. There is strong evidence that the similarity of the dynamic frequencies between large airplanes and slow-moving ships elicits this kind of control strategy from pilots. Similar experience has been reported for pilots of large ocean-going vessels by Nomoto (1957), and Fossen (1994). Sutton, Roberts, and Mort (1990) found a range of ships whose time constants suitably blend with and extend those of the largest currently flying airplanes.

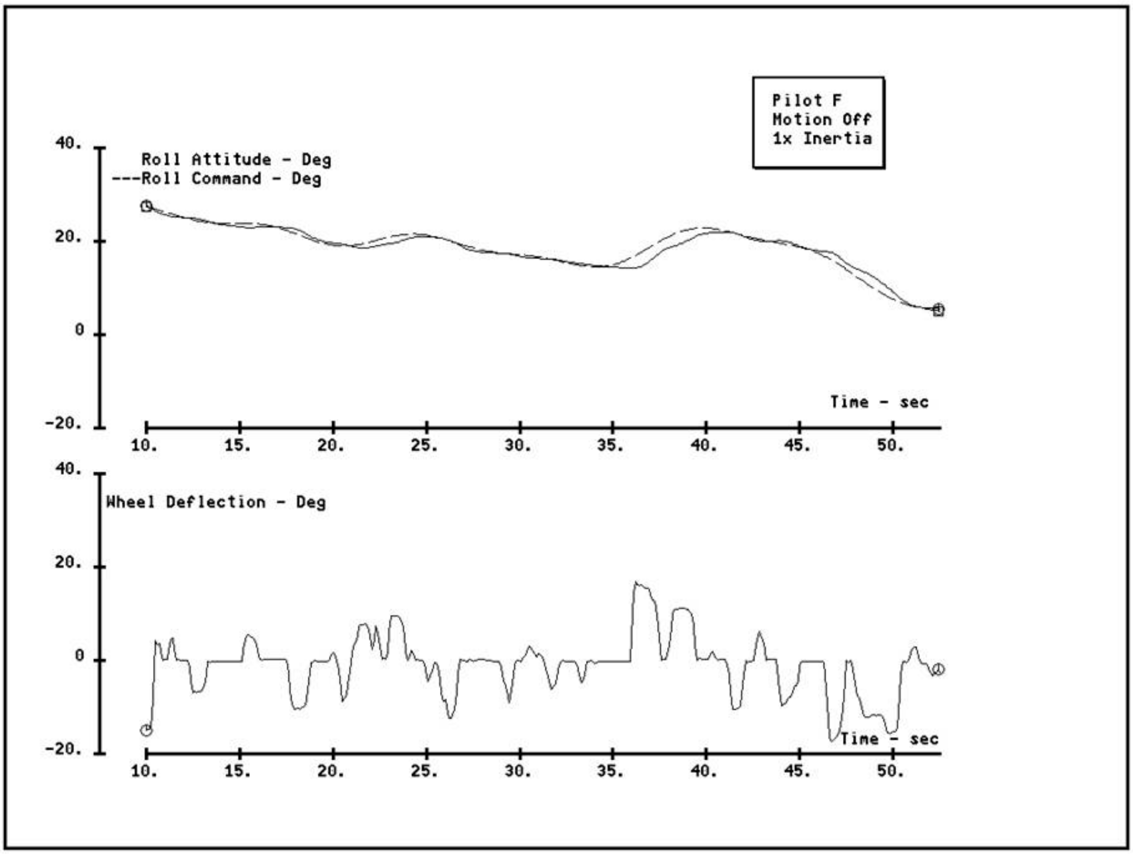

Figure 3-3. Slow Tracking Task

Besides the example shown here in Figure 3-3, Hess (1979) reported finding earlier work by Stapleford, Craig, and Tennant (1969) providing data showing pilot pulsive control behaviour in flying a jet transport. Hess compared that behaviour to similar control strategies found by other researchers for difficult control tasks and suggested that the use of a pulsive strategy could ease the pilot's computational burden for those difficult tasks. Hess also suggested a dual-loop model incorporating an "internal model" for the pilot, a feature prominent in the work of the Dutch ship-builders cited earlier.

3.3.3 Summary of Effect on Airplane Size

It has been seen that by examining the well-known modal approximations to longitudinal motion it becomes clear that as airplanes get larger, the short period gets slower and less damped while the phugoid would not be expected to change character purely as a function of airplane size. Further, it is seen that pilots have been observed to deal with slower-responding plants by implementing a pulsive control strategy. This has been observed in large aircraft and other large vehicles like ocean-going vessels. It has been suggested that in order for this control scheme to work, the pilot would need to have an "internal model" of the controlled element, and it has been postulated that a control strategy used in this way might ease the computational burden on the pilot. Importantly, there is no evidence that this strategy works or works well.

3.4 Relaxed Static Stability

Transport airplanes earn their keep by moving people and goods quickly and efficiently. Increasingly, as airlines struggle to reduce prices to gain business, they struggle more to reduce costs. For the newest transport airplanes, the target has been a 20% reduction in operating costs over the airplane it is to replace. As might be imagined, large reductions in operating costs require dramatic improvements in technology, so in the course of chasing performance, nothing is left off the table. While the bulk of performance improvements in the past have come from improvements in propulsion system efficiency, there is always pressure to continue to reduce weight and drag. The fact is that large static margins, larger manoeuvre margins, and large flight envelopes all require large control surfaces. These result in what management refer to as weight and drag "penalties".

3.4.1 Benefits of Relaxed Static Stability

In the aftermath of the global oil crisis of the 1970's, considerable research was conducted to find ways to reduce fuel consumption in jet transports. This research included significant evaluations of relaxed static stability. Numerous studies produced results suggesting that significant increases in efficiency could be gained by reducing the static margin on the airplane, and allowing the control systems to provide the necessary stability artificially. A sample result from one such study is presented in Figure 3-4.

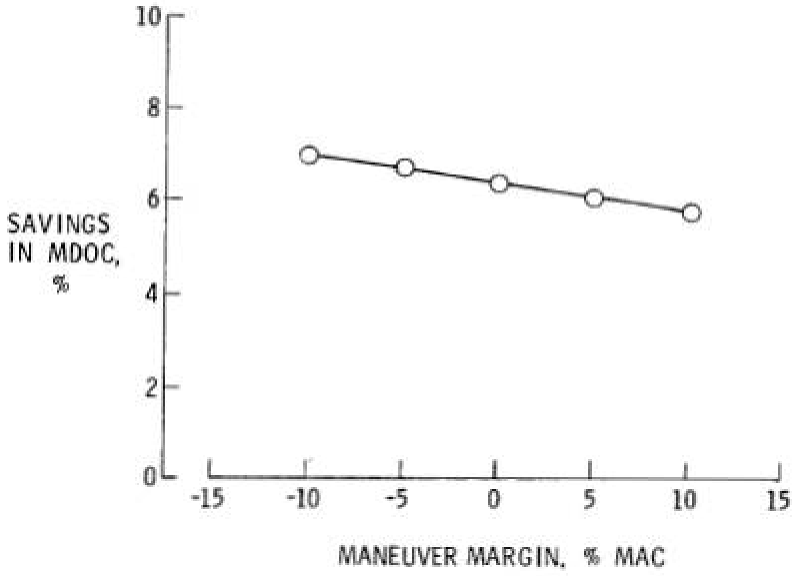

Figure 3-4. Economic Benefit for Relaxing Static Stability (From Sliwa, 1980)

3.4.2 Effect of Relaxed Static Stability on Dynamic Behaviour

During the 1980's there was a very large industry effort aimed at the "Energy Efficient Transport". This effort consumed half a billion dollars. Documentation is readily available: Boeing Commercial Airplanes (1980a, 1980b, 1980c, 1980d, 1981a, 1981b, 1982a, 1982b, 1982c, 1983a, 1983b, 1983c), Lockheed: Guinn, (1982, 1983), Guinn, Rising, and Davis, (1984), Guinn, Wiley, and Chong, (1983); McDonnell Douglas: Sizlo, Berg, and Gilles, (1979), and a host from NASA.

Perhaps the four most significant from the point of view of Handling Qualities were Weingarten and Chalk (1981), Schuler, (1983), and two volumes from Systems Technology: Hoh and Mitchell (1982) and Myers and McRuer, (1982). Weingarten and Chalk flew a number of configurations evaluating various augmentation schemes imposed on unstable airframe configurations. This very early look at million-pound-class airplanes concluded that pitch rate augmentation was preferred over angle of attack augmentation, that the pilots preferred (better ratings) to be far ahead of the centre of rotation, and importantly, that the pilots tended to apply a less demanding standard of manoeuvrability than for previous landing approach studies because

> "the configurations were defined to be very large, one-million pound, Class III aircraft"(p. 127).

Schuler collected enough data to declare the time-to-double requirement for the unstable root in the longitudinal axis to be an invalid requirement for Level 2/3 boundary, and proposed alternate criteria.

The two STI reports were under contract to the FAA, wherein the FAA asked for advice on certification of relaxed-static-stability airplanes. Hoh and Mitchell concentrated on the certification process aspects, including the philosophical decision to move towards "essential" augmentation. Myers and McRuer took great interest in one of the configurations flown by Weingarten and Chalk (the long, aft tail, high gain q feedback configuration) and the particular pilot ratings and comments this configuration generated. Myers and McRuer, after significant analysis on a similar configuration, issued a stern warning to FAA about the characteristics of so-called "super-augmented aircraft". In the long-aft-tail-high-q-feedback configuration, two pilots flew evaluations. One liked it. The other did not, until the second time he flew it. The pilot's comments were "It took me a while to get the airspeed and pitch attitude organized...". Myers and McRuer warned that even though the augmented short period is identical in form [same frequency and damping] to that of the airplane short period,

> "the parameters governing the response, however, are <u>entirely different in the origin</u>, <u>and may be significantly different in kind</u>."(p. 47).

What McRuer and Myers demonstrated was essentially that the "short period", or at least the mode that exhibited the desired frequency and damping to look like a short period was in reality the "third mode[§]" roots which had been pushed

[§] The presence of the mode known as the "longitudinal third mode" has been recognized for some time, if not widely discussed. Etkin's 1959 first edition (Etkin, 1959) demonstrates that as the CG is moved aft of the Neutral Point and the Short Period roots degenerate and begin to move along the real axis, the larger of those will encounter a former Phugoid root also on the real axis. As the CG moves further aft, these will become an oscillatory pair with a frequency usually between the former Short Period and the to a new location by the augmentation. McRuer went on to share his concerns about this with wider audiences at NASA and AGARD (McRuer, (1983), Myers, McRuer, and Johnston, (1984))

3.4.3 Summary of Effects of Relaxed Static Stability

There is significant economic benefit to reducing the natural static stability in airplane design, and the industry has recognized this fact for a long time. One consequence of relaxing the stability by reducing the tail size or by moving the CG aft, or both, is that the stability reduction must be restored, usually via a stability augmentation system. Another consequence is that the frequencies of the natural motion tend to decrease as the stability is reduced. This, too, is usually restored by stability augmentation. Yet another consequence which is known but not fully appreciated is that the character of the natural motion changes as stability is reduced. There have been warnings about this phenomenon, but very little study.

3.5 Aerodynamic Modelling

It is common practice in flight dynamics to represent the differential equations describing airplane motion in terms of aerodynamic derivatives, the forces and moments which are derived from airplane states or motion. In the derivation of these, it is also common to make use of the so-called quasi-static aerodynamic assumption. This assumption states that the lifting force on an aerodynamic surface can be represented as a function of its flight condition at any time. If the conditions change at another time, the aerodynamic load is assumed to change instantaneously to the new loading condition and the loads are integrated into forces and moments used in the equations of motion.

Cook (1997) explains clearly the assumptions on which this concept is based: that the derivatives are computed in the limit as the perturbation tends to zero.

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former Phugoid. Etkin points out that it is interesting but academic because nobody would ever build an airplane like that.

In this way, the aerodynamic derivative is defined without actually changing the flight condition (analytically).

In reality, though, and computationally as well, the flight condition does change, and not always in infinitesimally small increments. Hancock (1995) gives an elegant derivation of the changing forces from the perspective of unsteady aerodynamics. He points out that the quasi-steady load values are valid only after the motion subsides and an equilibrium condition has been achieved. He also points out that the loading during the motion itself is frequently modeled, e.g. in the lift direction, with the use of the $\dot{\alpha}$ term. Less frequently, but not uncommon in industry is the use of $\dot{\beta}$ terms and Hancock suggests the use of control rate terms as well.

With only a few well-defined exceptions, this quasi-static assumption has enjoyed widespread use. The primary exceptions include known "high frequency" phenomena like flutter and dynamic loads determinations in which the unsteady loading is computed explicitly as a function of time. What is perhaps not so widely appreciated is the effect of increasing airplane size on the applicability of the quasi-static assumption. Nothing could be found in the literature addressing this point.

Two aspects of large transport aircraft suggest that these notions should be revisited. The first is that they are large. The time standard for unsteady aerodynamic loadings is typically based on the chord length of the lifting surface: after some number of chord lengths have been traversed, the aerodynamic transients are assumed to have died out. When airplanes get large, and their chord lengths get large, so does the time it takes to traverse a given number of chords at the same speeds.

The second aspect of large transport aircraft to be considered is that being large, they are relatively slow to respond: their characteristic frequencies get very low. On one hand, this might be considered consonant with the larger chords, but on the other hand, pilots do not particularly like sluggish responses, so they tend to shape their inputs, overdriving the controls to induce faster accelerations. As airplane size has increased, a survey of the fleet suggests that flight control surface rates have not been reduced.

3.6 Actuator Modelling

The link between the control system and the aerodynamic force generation which feeds the dynamic equations of motion of the system is the flight control system actuator. On modern transport aircraft, these are generally hydraulic actuators which are commanded by a manual system (although with fly-by-wire systems becoming more popular, more and more of these will be commanded electrically). The issues of concern are similar: the mathematical models used for handling qualities analysis should be representative of the real system to the extent that it affects the results of the handling qualities analysis.

McLean (1990) derives from first principles a hydraulic actuator model with mechanical input and mechanical feedback, concluding that an appropriate model would look like:

$$\frac{x_{output}}{x_{input}} = \frac{K(l_1 + l_2)\omega_n^2}{s^3 l_2 + 2\zeta\omega_n l_2 s^2 + \omega_n^2 l_2 s + K l_1 \omega_n^2} \qquad (3.12)$$

in which the constant terms, along with ζ and ω_n, are functions of geometric and materials properties of the actuator, the fluid, and the surrounding support structure. McLean does not explicitly account for the mass or damping of the driven load which other authors do, but it is illustrated in his block diagrams and mentioned that it can be important.

McLean goes on to suggest that if certain parameters can be approximated and if the time constant can be made small enough, the actuator might be approximated to look like

$$\frac{x_{output}}{x_{input}} = \frac{K}{1+Ts} \qquad (3.13)$$

Similarly, Roskam (1979b) derives from first principles an electro-hydraulic actuator and shows that the equivalent open–loop transfer function is of the form:

$$\frac{x_{output}}{command} = \frac{K}{(\tau_1 s + 1)(s^2 + 2\zeta\omega_n s + 1\omega_n{}^2)} \tag{3.14}$$

Roskam similarly suggests that if the load is very small compared to the equivalent damping of the fluid flow and the natural frequency of the actuator is significantly higher than the load/equivalent damping, then the actuator can be approximated by a first order form. These assumptions are important and may not be applicable to large jet transport aircraft.

3.7 Pilot Feel Characteristics

This discussion of feel systems is intended not so much as a description of various system components and their installations and the philosophies guiding them; the intent is rather to focus on the effects on the pilot's ability to use the controls to command the flight path of the airplane, and their ability to provide both the required feedback to the pilot and stability and damping for the airplane. Nevertheless, in order to make sense of the role of the artificial feel system in modern jet transport aircraft, it is helpful to review some aspects of mechanical controls.

For airplanes with reversible, mechanical control systems, the pilot's commands as well as the airplane's dynamic response are determined at least in part by the mechanical characteristics of the control system itself. When the pilot wants to command a control input, a force is applied to the control inceptor (whether that is a centre stick, a wheel/column (e.g. Dep. Control) or a sidestick). This force acts through the equations of motion of the system itself to move the mass of the mechanical control system itself and once the surface starts to move, is opposed by the aerodynamic hinge moment generated. For the purpose of illustration, consider the mechanical system of Figure 3-5, borrowed from Roskam (1979a).

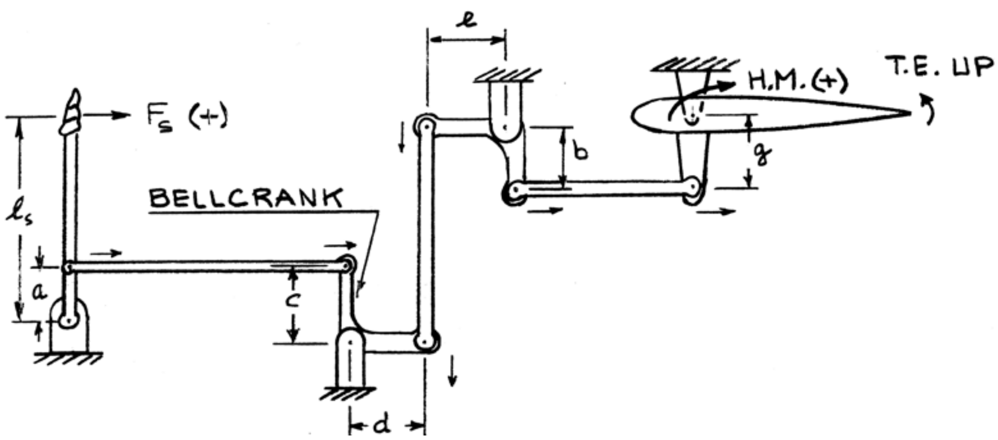

Figure 3-5. Simplified Mechanical Control System Layout. (Roskam, 1979a)

A survey of this kind of system gives light to the various elements in play. Even for the most simple systems, the pilot must be able to command the control surface position to generate the required manoeuvring loads, that must take place against the aerodynamic hinge moments in play at the time. All mechanical systems will come with their own mechanical "baggage" in terms of friction. Many times mechanical dampers will be added as well. In addition to the aerodynamic hinge moment loads imposed, many even simple systems will incorporate springs to provide centring and often times for stability enhancements. All of these features add mass to the system to be moved by the pilot.

To this, some systems include extra masses of surface balance weights (added for flutter suppression), bobweights, for manoeuvre stability enhancement, manipulator mass balance weights[**], etc. An example of a column mass balance weight is illustrated in Figure 3-6 for a centre-stick controlled fly-by-wire transport; Figure 3-7 for a column-wheel controlled fly-by-wire transport. The net result of these masses and the forces in the system defines the system's dynamic characteristics (e.g. natural frequency and damping). In general, weight is a bad thing in airplane design, and is usually minimized. It is typical

[**] For a conventional control column, most of the mass is above the pivot point. At large longitudinal accelerations, and large nose-up pitch attitudes, this unbalanced mass can have a tendency to pull the column aft, by applying an inertial load. For this reason it is not uncommon for control columns to be mass balanced. Similarly, bobweights, when used, are frequently applied "symmetrically" ahead of and behind the instantaneous center of rotation (ICR).

that control system masses, though, are considered mandatory (although managers will frequently argue with things like column mass balances because they don't like carrying dead weight around). As a result, the system characteristics are typically defined by the static force levels; the dynamics (e.g. frequency and damping of the system itself) tend to fall where they will, and as long as they don't interfere with flutter margins, are generally left alone.

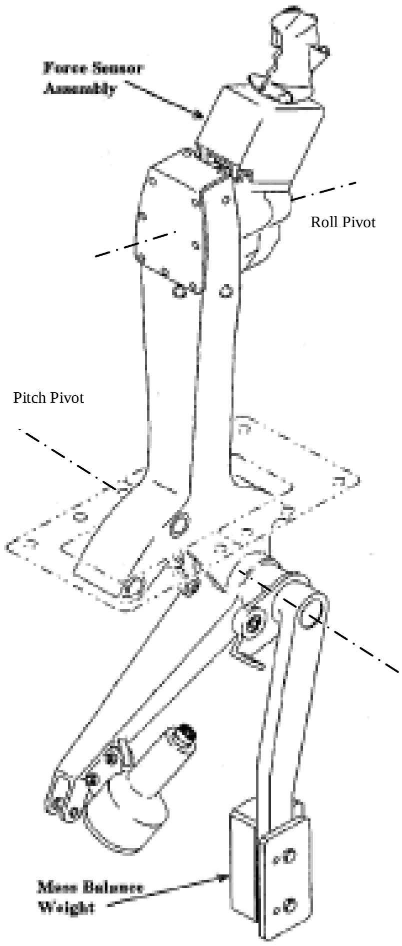

Figure 3-6. C-17 Control Stick
(Iloputaife, et al, 1996)

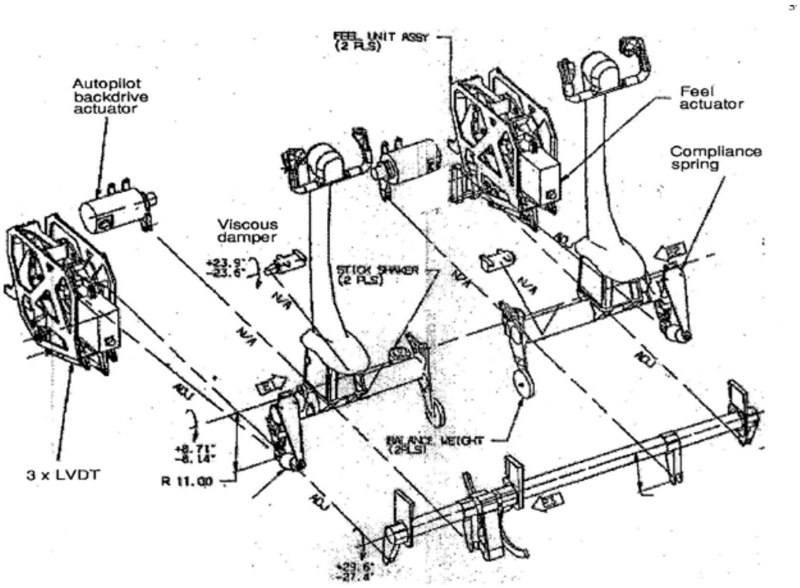

Figure 3-7. 777 Cockpit Control Wheel/Column.
(Gibson and Hess, 1997)

When the pilot is the source of the force input to the controller which must overcome the inertial and aerodynamic forces, the limitations of the human pilot become the designing inputs. Both the military specifications and the civilian certification requirements levy maximum forces to be expected from pilots in operation. (Structural strength design requirements for system components, so that the pilot will be unlikely to break anything in the system are specified separately, and are considerably higher than the operational force limits.) Unfortunately, these specifications and requirements for the most part only specify maximum forces; other forces must be inferred from the regulations.

3.7.1 Requirements on Static and Manoeuvring Forces

The origins of numerical limitations on forces that pilots could be expected to exert lie in early NACA work. Gough and Beard (1936) conducted research in a cockpit mockup to generate force levels. This work was extended to wheel controls by McAvoy (1937). Gough and Beard’s experiment included the possibility of rolling the cockpit through 180 degrees to evaluate the effects of orientation. McAvoy’s study included having the pilot restrained by seat belts/shoulder harness or not.

This work has been continued and comprehensive summaries are included in the BuAir reports (1954), and another summarized by Latham (1956).

Effects of Aircraft Size and Speed Range

Obviously a significant portion of the pilot force in purely mechanical systems is due to the aerodynamic hinge moments themselves. The total force the pilot exerts on the controller to generate a command to the airplane system can be represented rather generically by:

$$(m_{system} + m_{\lim b})\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta} + F_{Fr}\ \mathrm{sgn}(\dot{\delta}) + F_{Br}\ \mathrm{sgn}(\delta) = F_{Pilot} \qquad (3.15)$$

For a purely mechanical flight control system, the aerodynamic hinge moment on the control surface must be overcome by the pilot, and it is represented in Equation 3.15 by the term F_{δ}. Aerodynamically, the static hinge moments to be overcome at any given deflection can be represented by:

$$F_{\delta} = G(HM) = G\overline{q}_e S_e \overline{c}_e C_{h_e} \qquad (3.16)$$

One important point here is the dependence of the required force level on dimensional airplane size. The hinge moment is a direct function of the control surface area and the chord (in this case the elevator, S_e and c_e, respectively). For large airplanes, these become numerically large.

A second important point here is the dependence of the resulting pilot force on true airspeed via the dynamic pressure term $\overline{q}$. For airplanes with a large speed range, since $\overline{q} = \frac{1}{2}\rho V_T^2$, the stick force for a given deflection can also become quite large. Moreover, for airplanes with large speed ranges, it can be quite challenging to find a hinge moment characteristic (C_{h_e}) which provides adequate feedback at low speed, and not produce excessive forces at high speed.

On the other hand, increasing stick force per degree of deflection has a positive benefit in terms of tactile feedback to the pilot regarding the airplane's energy state. Stick force stiffening with speed has the effect of helping to "protect" the structure from overload in the event of inadvertently large or overly aggressive pilot inputs. Norair (1953) points out that this is one "feature" (stick stiffening with speed) from mechanical reversible controls which has a significant place in artificial feel systems design, as it provides not only structural load protection, but tactile feedback to the pilot regarding the flight condition, as well.

As airplanes have grown in size and speed capability, the challenge of managing the hinge moments (pilot force levels) has also grown. Aerodynamicists have relied on a large number of design solutions to manipulate the aerodynamic hinge moments ranging from overhang and horn balances to a surprising array of internal balance and tab devices. Careful design of these hinge moment characteristics was discussed in detail by Lee (1988, 1990).

Abzug and Larrabee (1997) cites a reference to Orville Dunn in 1949 giving 30,000 lbs as a rule-of-thumb upper limit on weight of airplanes with purely mechanical controls using leading edge aerodynamic balances. Above that weight Abzug and Larrabee reported that Dunn suggested tabs or hydraulic boost would be required.

The largest and fastest airplane in the West with purely mechanical control systems was probably the B-52 (nearly 500,000 lb takeoff weight, 400 knots at sea level). Even though this airplane is distinctly non-manoeuvrable, and not "easy" to fly precisely, it was made possible by significant tailoring of the hinge moments including sophisticated internal balances. In the commercial world, the Boeing 707 flew on mechanical controls, as did the Heritage Douglas products (tab driven). These airplanes were considerably more manoeuvrable, although not quite as big (~350,000 lbs.) and not quite as fast.

Beginning with the later model 707's (rudder) and as standard production for all three axes on the 727 and 737, Boeing's commercial transports made use of hydraulic boost to ease the control forces required of the pilot. These airplanes, however, retained the mechanical cable connection between the pilots' control inceptors and the aerodynamic surfaces as a means of redundancy management. Beginning with the 747 in the late 1960's, Boeing made the transition to fully irreversible primary flight controls, with the control inceptors connected via cables to hydraulic valves, which then moved the surfaces.

More important for this discussion, though, is the impact on handling qualities produced by breaking the purely mechanical link between the pilots' control inceptors and the control surface position. With the hydraulic actuator inserted in the control link, all feedback to the pilot of the control surface loading (the tactile cueing noted above) is lost. Further, with the introduction of stability and command augmentation on fly-by-wire control systems, the connection between the control surface position and the control inceptor position is also lost.

The benefit of this tactile feedback, or rather the danger if it should be lost, was seen dramatically in the accident of a Greek Falcon 900B (Tocu, Charalabakis, and Cohen-Nir, (2000)) in which several passengers were killed as a result of the loss of control ensuing from the lack of suitable feel characteristics (a feel system failure). Flight Data recorder data from this accident is reproduced in Figure 3-8.

The Flight Safety Foundation (2001) reported a similar incident, in which the "PITCH FEEL" light had flickered, and the airplane experienced a violent PIO at high speed when the pilot over-rode the autopilot.

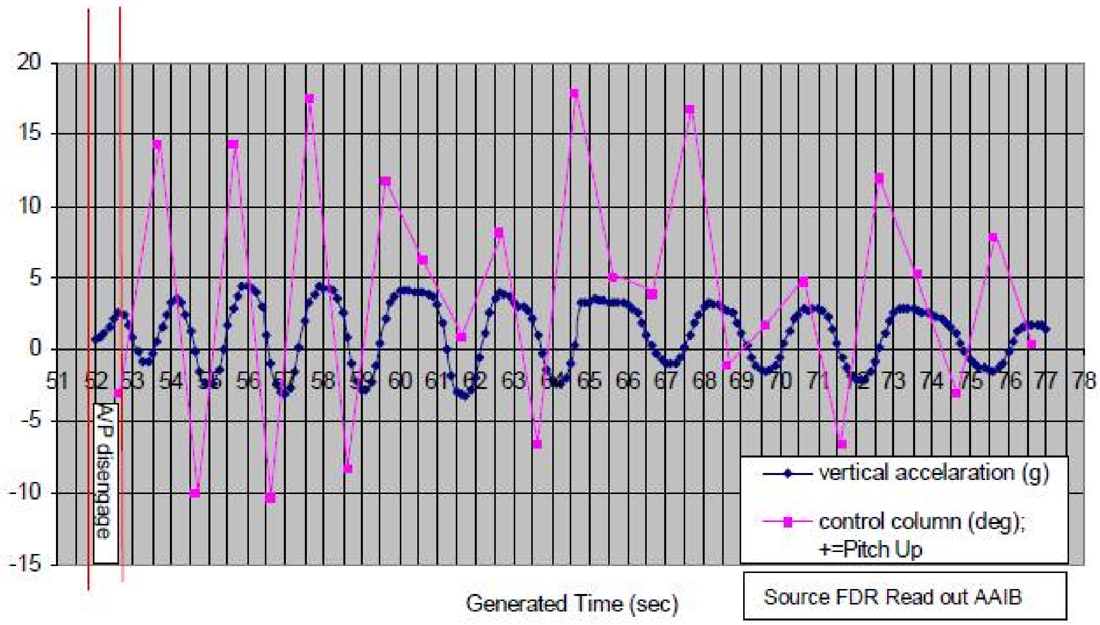

Figure 3-8 Greek registered Falcon 900B experienced a severe PIO following autopilot disconnect with a failed feel unit. (Tocu, Charalabakis, and Cohen-Nir, (2000))

In order to replace the tactile feedback lost to hydraulic actuators, on airplanes with irreversible controls, the characteristics of the control inceptor (as well as the relationship to the airplane dynamic response) deserve special attention. The hinge moment equations, and perhaps even the balances and tabs are not necessarily gone, because tabs and balances still can be effective in reducing hinge moments and therefore reducing weight and power required of the system to drive them. Another reason that aerodynamicists still need to pay attention to hinge moment characteristics, even in the presence of fully powered controls is that the actuators must be sized properly not only to produce the static hinge moment necessary to move the surface, but enough to move it, under load, at the proper rate.

Feel System Research

Early work on artificial feel systems came along with the first hydraulic boost systems. In the US, one of the best documented experiments of this type was an attempt to reduce the pilot control forces on the Boeing B-29, reported in

(Mathews, 1951). This study examined the dynamic response of the control system and found pilots of the day were so eager to reduce the control forces that they were willing to give up on some control rate capability to achieve the reduced forces.

More modern, and more important was the work done at Calspan by Smith and Sarrafian (1986) in which they discovered that time delay originating from the feel system was not as significant to pilots as that originating further downstream in the system. This and three other studies (Bailey and Knotts (1990), Watson and Schroeder (1990), and Morgan (1991)) was reviewed by Mitchell, Aponso, and Klyde (1995). Mitchell, et al concluded that the impact of cockpit feel dynamics do have an impact on flying qualities, although the database is rather sparse and the results are a bit "idiosyncratic". Mitchell suggests that further research is justified.

Just two years later, Gibson and Hess (1997) published a thorough review of stick and feel system design including detailed discussion of mechanical component details, handling qualities implications, and analysis via pilot modelling techniques. They conclude, like Mitchell, et al that more research is justified.

Requirements on Force Characteristics

Both the civilian authorities and military procurement agencies levy detailed requirements on the force characteristics. These are discussed in Appendix D. Similar to the discussion of dynamic characteristics, the civilian requirements are quite qualitative, only serving to ensure that forces do not get too large or too small (the effect of getting too small has been seen in the Falcon accident noted earlier). Importantly, the emphasis is on the total force and force characteristics during prescribed manoeuvres, e.g. elevated load factor, or reducing speed. No detailed advice is given on friction/breakout/gradient combinations.

Military requirements do provide at least some reference to these details (e.g. breakout force), but only providing broad ranges which seem to have been found acceptable.

3.7.2 Feel System Linearity

The presence of nonlinear elements in control systems and in particular in force feel elements has been known and acknowledged for decades. Further, despite the sporadic attempts to deal with them analytically which have similarly been around for decades, the fact remains that they are still there, they are not amenable to linear analysis, and the typical industry response is to try to minimize them so that they can be ignored in analysis. In many cases, these elements are in fact necessary countermeasures inserted deliberately to deal with such realities as mechanical friction or pilots' inability to discern very, very small changes in force levels (see, e.g. Gibson and Hess, 1997). Yet, the allowable intrusion on acceptable linear characteristics remains for the most part unquantified.

Consider a conventional wheel controller used for lateral flight control. In manual control, the application of a torque to the wheel (or force at and tangential to the grip) would be expected to produce a rotation of the wheel. For reversible control systems, this deflection would be restrained by aerodynamic hinge moments fed back through the control mechanism and felt by the pilot as a restoring force, driving the controller back to neutral. Indeed, positive centring is a desirable attribute for lateral controls. For irreversible control systems, this force feedback and centring is usually generated by an artificial feel system of some sort. One challenge for the designer is to specify the magnitude and character of these forces to contribute to good handling qualities.

In the simplest idealization, the relationship between required wheel force and wheel deflection would be linear, as shown in Figure 3-9. This relationship makes analysis of the force-to-deflection characteristics straightforward, and the only parameter to be selected in design is the spring constant.

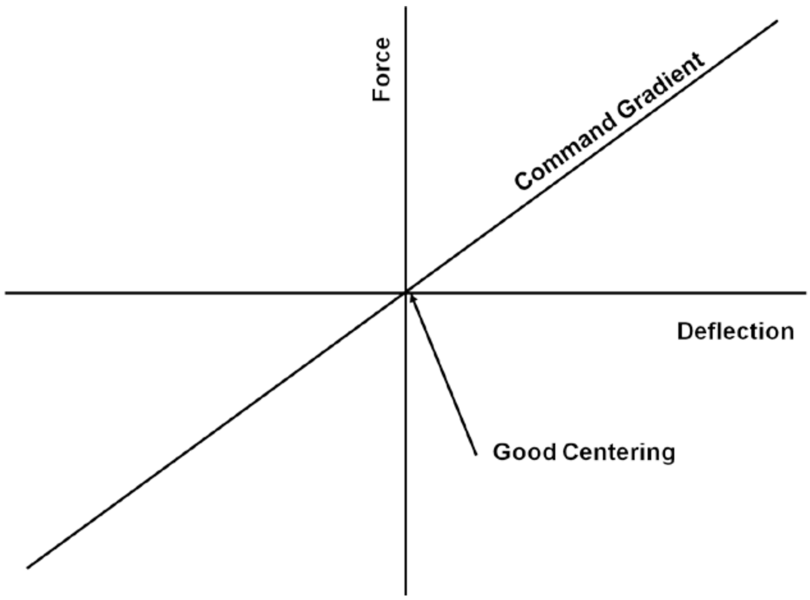

Figure 3-9. Good, Linear Force vs. Displacement

Unfortunately, for mechanical systems, this idealization is simply not representative of the actual system characteristics, and the differences do have an effect on the operation of the system. The principal difference is the effect of friction (although deadband, backlash, nonlinear gradients, and other elements may also be present). The effect of mechanical friction, illustrated in Figure 3-10, is to produce hysteresis throughout the entire deflection range, and one result is poor centring, as can be seen.

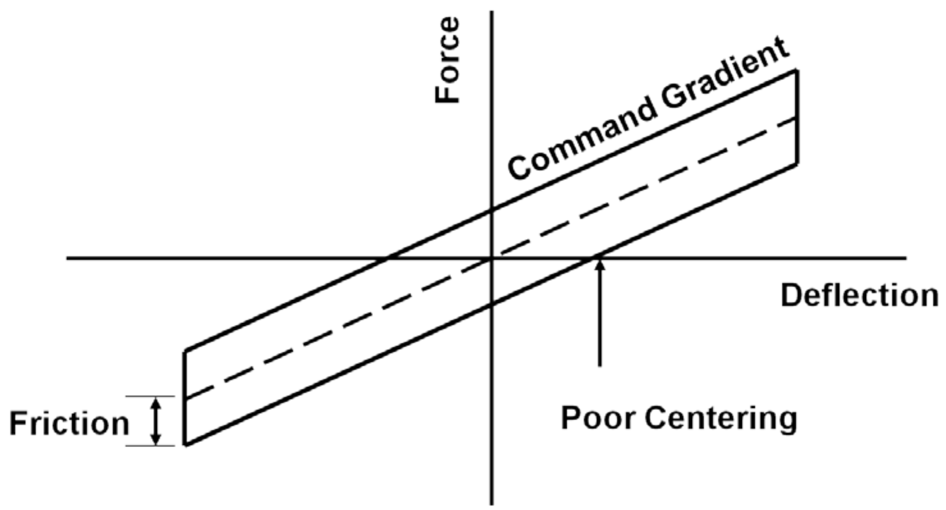

Figure 3-10. Effect of Friction.

A typical response to the poor centring resulting from friction is to include a separate "breakout" detent or centring spring. This typically has the effect of offsetting the entire hysteresis loop so as to generate positive centring, as shown in Figure 3-11. If the gradient of this extra centring spring is steep enough, the presence will be felt over only a very small deflection range. In addition, if the magnitude is small enough, the effect may well mimic that of "static friction" sometimes referred to as "stiction", a very natural element in mechanical system motion, which pilots may accept as "normal". In addition, the presence of a centring detent, or a force bump at zero wheel, is regarded as useful because it gives the pilot a tactile indication of precisely where zero wheel deflection is. This allows the pilot to sense neutral wheel without looking at it, and the availability of this information via a tactile cue represents a workload reduction for pilots.

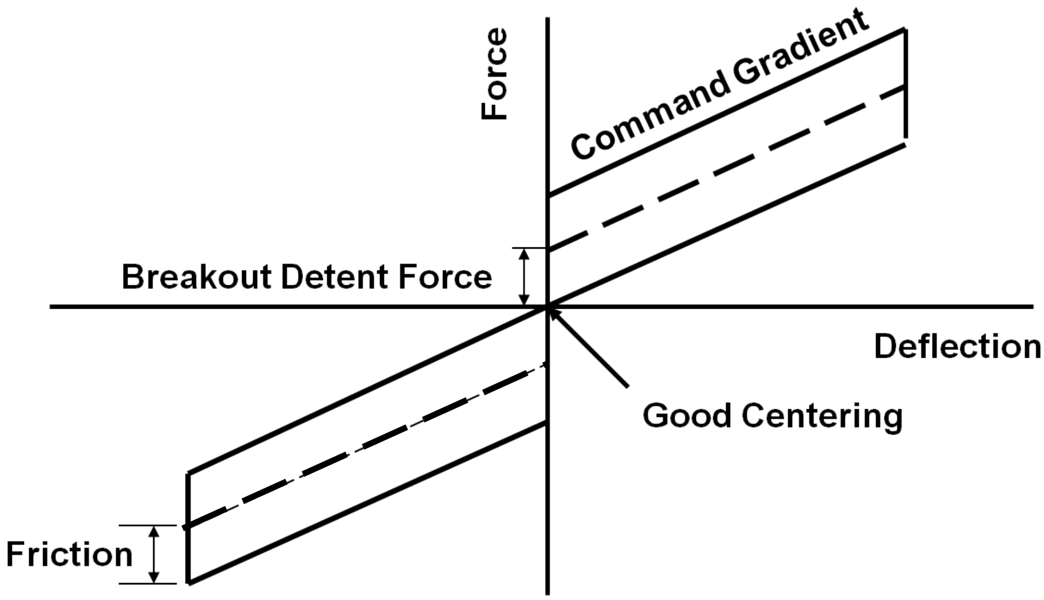

Figure 3-11. Offsetting Friction with Breakout

The manifestations to the pilots of these and other nonlinear elements between the pilots' fingers and the airplane dynamic response were discussed in Lee, (2001), and include the introduction of several force/deflection/response ambiguities.

Consider first the effect of breakout, or the offsetting of the entire friction band, as illustrated in Figure 3-11. As noted above, the addition of this feature usually produces positive control centring in the presence of friction. For purposes of illustration, Figure 3-12 represents a case in which friction is zero and a large breakout detent has been added. Part of the price to be paid for this addition is a typically very distinct change in gradient right at the breakout point. In order to keep the total breakout force to a minimum while insuring centring, the breakout gradient is usually very large. This also means that the difference between the breakout gradient and the command gradient will be maximized.

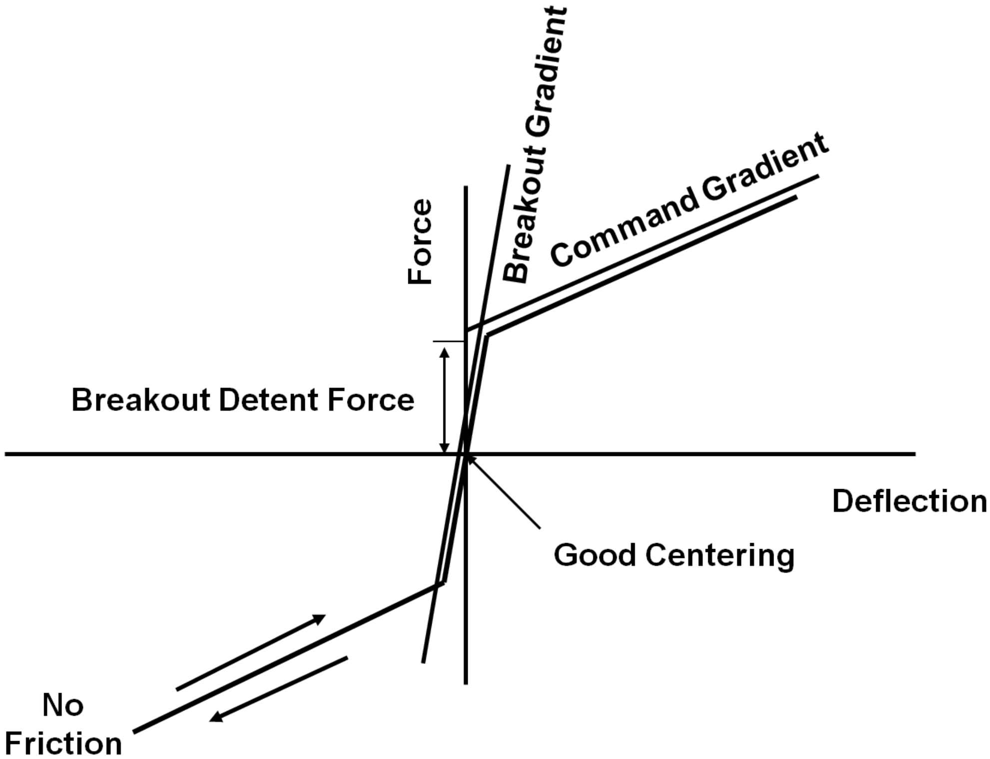

Figure 3-12. Breakout Detents Generate Gradient Ambiguity

Force/displacement discontinuities are generally regarded as being detrimental to handling, principally because predictability in the force/displacement loop is compromised. In order to achieve a particular displacement, the pilot must apply a force to the manipulator. Just how large a force to apply, though, is initially a judgment by the pilot, followed by the pilot closing a loop around displacement as he decides how much force to apply. This is quite consistent with the findings of van Passen (1994) which suggest that pilots need an internal model of the system they're controlling in order to predict the appropriate force inputs to make precise loop closure.

Gradient changes in the range of motion, particularly in which the force gradient decreases, even though the total force is increasing, generally result in overshooting in position or deflection. In the case of imbedding a breakout force at neutral wheel, this very large gradient change is right in the middle of the displacement range, where the pilot might reasonably be expected to be trying to make very small deflections in the course of tight tracking manoeuvres.

Previous work by the author investigated this for a particular wheel controller and demonstrated this effect, as illustrated in Figures 3-13 and 3-14, taken from Lee, (2001). In this experiment, the task was a simple one-degree of freedom tracking task in which the pilot was asked to move the wheel to a particular position in response to a verbal command (one unit left, two units right, four units left, centre, etc.). What is illustrated in Figures 3-13 and 3-14 is the tracking result, with wheel position on the top and wheel force on the bottom, both as functions of time. Both runs were made with the same sequence of commanded wheel deflections, and these data are near the end of each run. The full Left wheel deflection is shown about a third of the way across the time history on Figure 3-13, while it is near the vertical axis on Figure 3-14.

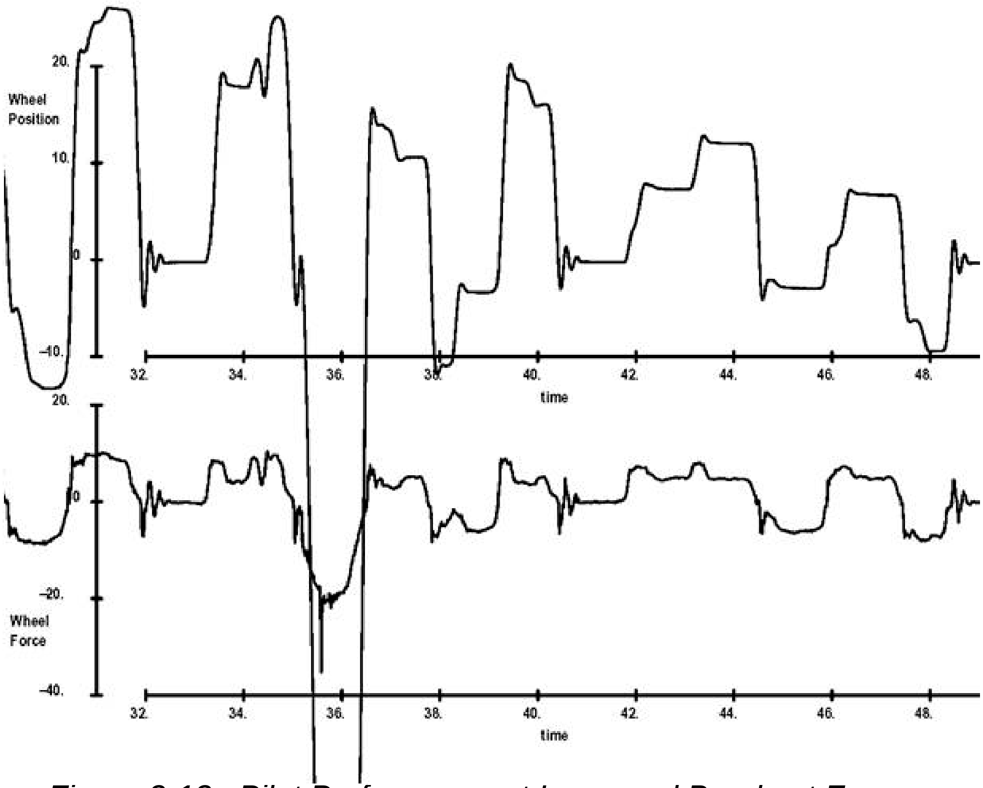

Figure 3-13. Pilot Performance at Increased Breakout Force

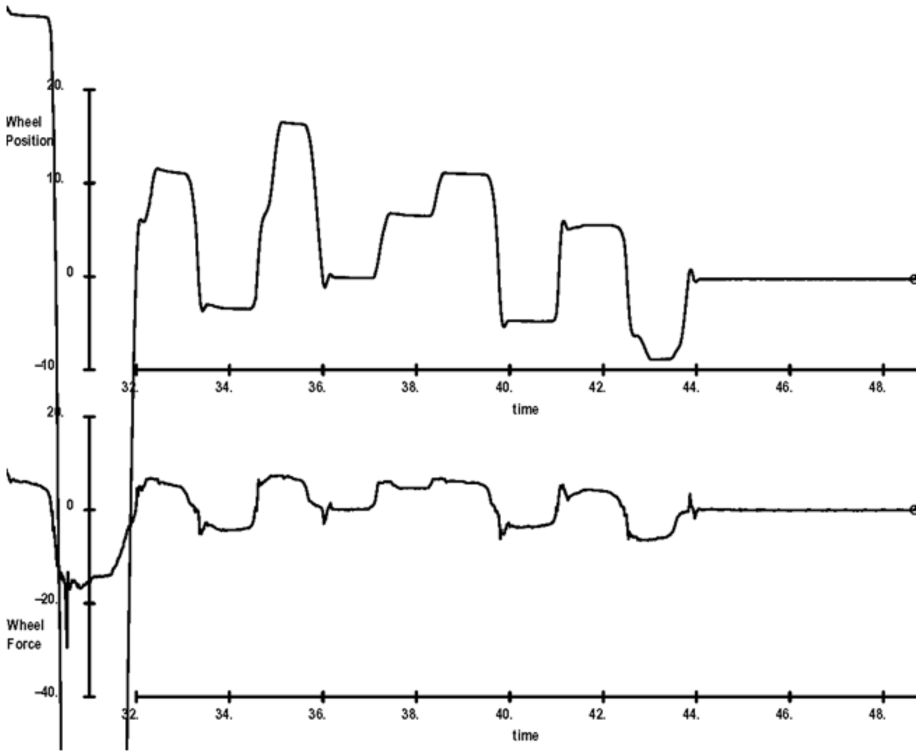

Figure 3-14. Pilot Performance at Decreased Breakout Force.

Comparing the two figures illustrates the difference in tracking performance for a one pound change in breakout force at the same spring gradient. The breakout force in Figure 3-13 is one pound greater than that of Figure 3-14. (Both are within the guidelines of MIL-HDBK-1797, (US Department of Defense, 1997).) It is evident that the pilot's ability to precisely position the wheel in response to verbal commands is significantly affected by the level of the breakout force present.

While the pilot appreciates and gets additional information from the presence of a tactile detent force at neutral wheel, there do exist some threshold values. If the detent force is too small, particularly in the presence of large friction and large system inertia, the pilot will not be able to feel the presence of the detent (not to mention the possibility of poor centring). If the detent force is too large, pilots report that the detent "gets in the way" of precise manoeuvring. Specific threshold values should be determined by testing for each particular manipulator installation in question.

The presence of a breakout detent force improves centring and provides tactile cueing, but it also represents a nonlinearity which can deteriorate the pilot's opinion of the handling qualities.

Consider next, the presence of friction, as illustrated in Figure 3-15. Particularly when operating around a trim point away from neutral as in, for example, a slipped crosswind landing, the pilot might find himself holding a wheel force, at point 1. If, in order to manoeuvre about that point, the pilot needed to deflect the wheel more in the same direction, say, to point 2, he may be operating on the command gradient. If a gust then required a small deflection in the direction towards neutral wheel, the effective gradient from the trim point to points 3 or 4 is a function of the size of the input required. This complicates the pilot's control problem, because now the force/displacement relationship is continuously changing. The gradient ambiguity generated by the presence of friction is obviously a function of the size of the friction band.

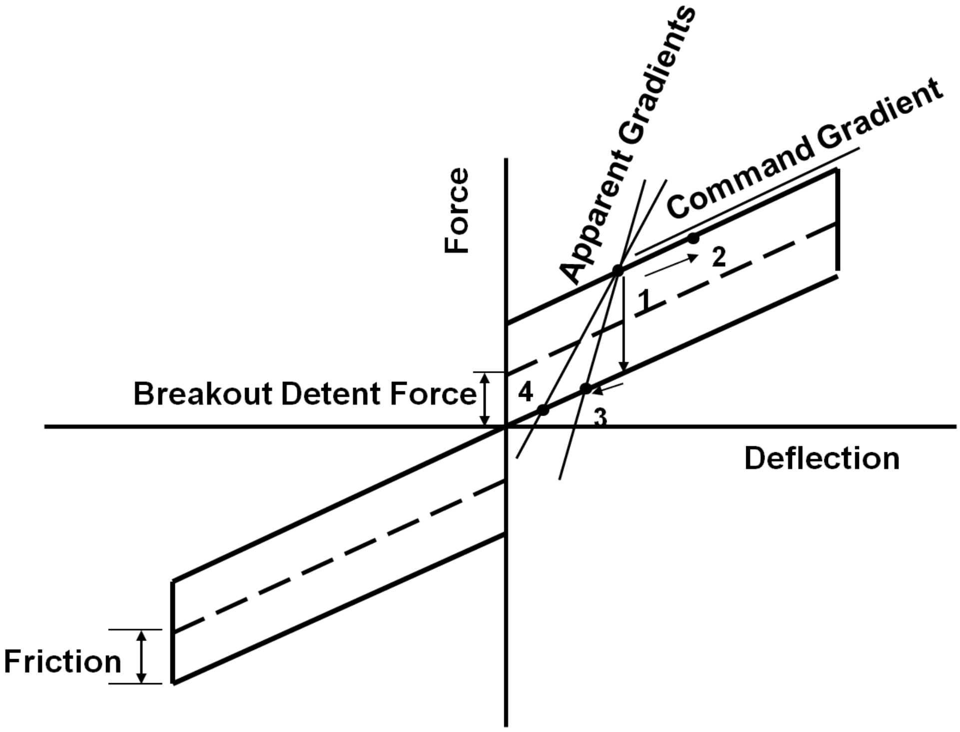

Figure 3-15. Ambiguity Resulting from Friction.

The effects on handling qualities of friction are dependent on the individual control manipulator and its mechanical implementation. Threshold values should be determined for each manipulator and installation experimentally. Despite the evidence cited in, for example, Gibson and Hess (1997) that many pilots can indeed deal with the force/displacement ambiguity presented by the presence of friction, the fact is that they don't particularly like it. This is evidenced by the degraded pilot ratings for large friction values given in Lee, Rodchenko, and Zaichik, (2003).

Hess's Linearity Index

Hess, in his evaluation of different system characteristics for rudder pedal control (Hess, 2004) noted a difference in closed loop responses as a function of these nonlinear elements. In order to characterize the results he found, he suggested a "linearity index" as a figure of merit, or way of quickly classifying the linearity of a system. In (Hess, 2004), Hess suggests a non-dimensional linearity index, given by

$$LI = 1 - \frac{Area(DABD) + Area(DBCD)}{Area(DEBFD)} \qquad (3.17)$$

Where A, B, C, D, E, and F are defined in Figure 3-16, adopted from Hess (2004). Defined in this way, the linearity index is geometrically a measure of the area of DEBFD taken up by the friction band, DABCD.

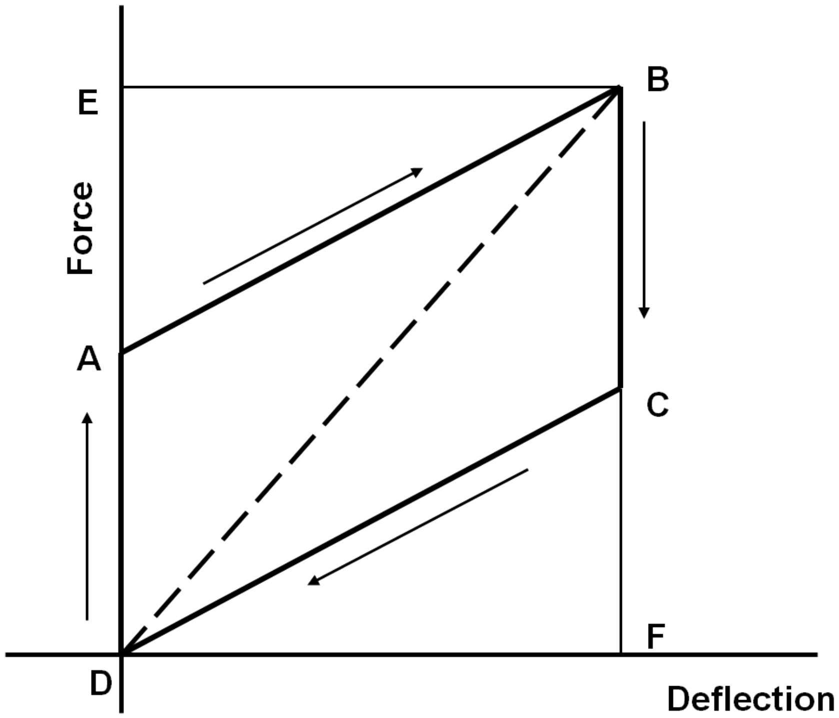

Figure 3-16. Hess' Linearity Index Definitions.
(Adapted from Hess, 2004)

An analysis of Hess's Linearity Index is given in Appendix E. What it shows is that while Hess's index generates a numerical value to characterize the linearity of a system, it is limited in that it is only applicable to cases in which friction is equal to breakout, and it cannot distinguish the sensitivity difference between increasing force at constant deflection or increasing deflection at constant total force. Nevertheless, it is an interesting notion, and will be addressed further in Chapter 4.

The Construct of "Sensitivity"

Airplane handling qualities practitioners are well familiar with static, open loop sensitivity parameters like roll rate per inch of control deflection or roll rate per pound of control force in the lateral axis or stick force per g or pitch acceleration per pound of control force in the longitudinal axis. These measures indicate the slope of an input/output relationship between two parameters, usually a pilot input parameter and an airplane response parameter. For airplane dynamics, for example, the slope of roll acceleration per pound of wheel force or per degree of wheel deflection define such relationships. Limits on these slopes are commonly referred to as sensitivity boundaries.

Limits on controller sensitivity are usually bounded by precision and workload. In the displacement dimension, the lower displacement sensitivity (e.g. small value of roll acceleration/inch of wheel travel) is bounded by physical workload required to throw the manipulator around. The upper bound (e.g. large value of roll acceleration/inch of wheel travel) is typically bounded by a precision control requirement. This involves answering the question "how small a deflection can the pilot make deliberately to get the desired roll performance precisely without inadvertently overdriving the controller?". The latter involves also an assessment of external disturbances, and the effect they might have on the pilot's ability to precisely control movement of the inceptor.

In the force dimension, the bounds are similar. At low force sensitivity (e.g. small value of roll acceleration/pound of wheel force), the pilot finds that the physical workload involved in manoeuvring is too great. At high force sensitivity (e.g. large value of roll acceleration/pound of wheel force), the pilot finds that he has difficulty regulating his force inputs to a high enough resolution to make precise commands.

This goes right to the heart of the question of whether pilots use controller force or position to fly airplanes. One expert is quoted as describing the answer as being "yes, and we do not know when", implying that pilots use both force and position feedback from the manipulator in their flying of the airplane, and we do not know when one or the other is more important. This position is held so strongly that the requirements of (US Department of Defense, 1997) specify both.

So the challenge of the controls designer is to find the right combination of force and displacement sensitivity so that both are reasonable for the pilot, and both are in consonance with one another. Recent work (e.g. Lee, Rodchenko, and Zaichik, 2003, and 2004) have demonstrated that force feel and airplane dynamic response to a position controller are indeed closely related in terms of pilot opinion, but in a very complicated way.

In referring to system elements in isolation (like feel systems), it is difficult to address "sensitivity". If the generalized definition of the slope of an input/output relationship were applied to a position controller, the only parameters available to use for such a definition are force and displacement. This naturally produces a definition of sensitivity (for the manipulator feel system alone) of force/unit deflection. Taken in isolation, the numerical value of this sensitivity parameter can be changed by altering either force or displacement.

Force or Displacement: some data

There has been considerable debate in the US regarding the question: "Does a pilot use controller force or controller deflection in order to pilot an aircraft?". The answer appears to be "yes, but we do not know when". Some work conducted in Russia, however, can shed considerable light on this question. While there is no simple answer, some help can be found in the data and the theoretical approach developed there.

Figure 3-17 shows normalized force sensitivity plotted against normalized deflection sensitivity from Efremov, et al (1992). Plotted on this figure are the Level 1 (PR<3.5) boundary and the boundary of best handling qualities (PR<2). The radial lines represent spring gradients (friction and breakout are constant), and represent gradients from 0 (no spring at all) to infinity (no motion at all). This data shows that the region of the force-displacement map in which the best handling qualities were realized is that in which *both* force and deflection cues were presented to the pilot. The combination of forces and deflections which resulted in the best handling qualities provide favourable conditions for muscle function and resulted in the best dynamic performance of the sensiomotor apparatus. When the forces and displacements increase, pilot ratings deteriorate due to limitations of the human's ability to generate large forces and/or large deflections; when forces and displacements decrease, pilot ratings deteriorate due to difficulties in "measuring out" the control inputs, significant interference by involuntary pilot controller motion, etc.

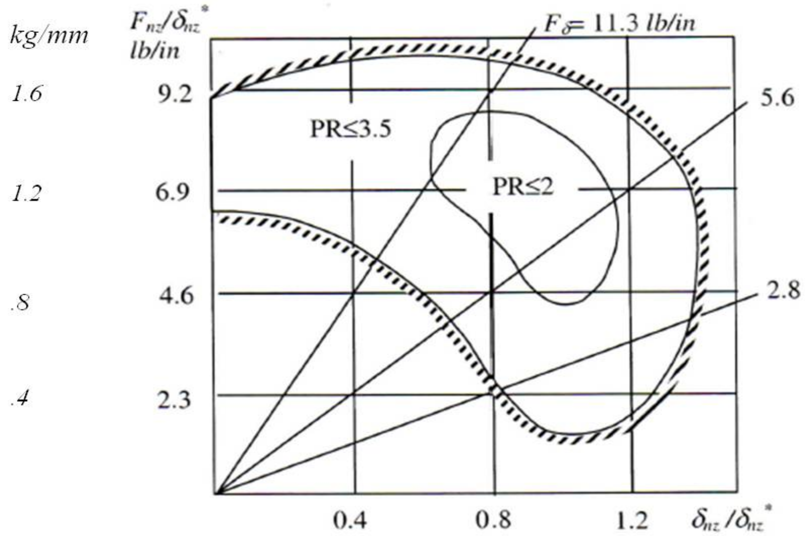

Figure 3-17. Handling Qualities Boundaries for Force and Deflection (Efremov, et al, 1992)

It was observed during the collection of this data that when the spring gradient increases beyond a certain value, pilots begin to maintain a constant force sensitivity. In other words, they "switch" to a control strategy in which they command a control force. When the spring gradient decreases below a certain value, pilots prefer a control strategy dominated by commanding primarily a deflection. This observation is consistent with that seen in the West, with various controller types and various aircraft classes.

Significant in the results of Figure 3-17 is the fact that the absence of column displacement affects pilot ratings to a lesser extent than the absence of column forces. In Figure 3-17, the Level 1 boundary does not approach zero values of spring gradient, but it does extend to zero values of deflection. Importantly, while this data was collected for a centre control column, similar results have been found for sidestick installations, and reported in Rodchenko, et al, (1994a, 1994b)

The question of fixed or variable feel or gearing is illustrated using the same data as Figure 3-17, in Figure 3-18. In (1), the vertical arrow corresponds to the case of variable feel and fixed gearing. This suggests that there is a range of feel gradients at fixed gearing which are acceptable to pilots. In (2), the inclined arrow running along a single spring gradient corresponds to the case of variable gearing and fixed feel. This similarly illustrates the fact that it is possible to select a range of gearings with fixed feel which are acceptable to pilots. In (3), the curved arrow illustrates a case of variable feel and variable gearing, present in some Russian airplanes. The important point, though, is the fact that in each of these cases, pilots deal with *both* forces and displacements.

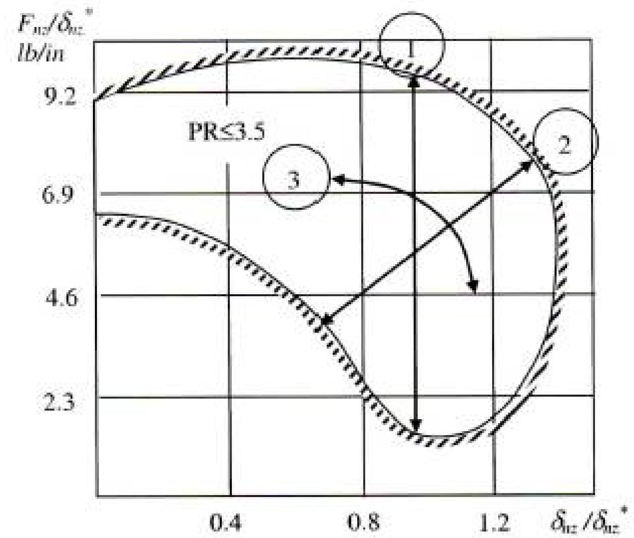

Figure 3-18 Variations Created by Fixed or Variable Gearing.

Dynamics of the Controller

It was noted at the outset of this discussion of controller characteristics that controllers have mass, and the relationship between force and displacement is subject to the equations of motion of the system itself. While the military requirements (US Department of Defense, 1997) do specify that the buildup of force may not lag the acceleration cue at the cockpit, there is very little in the literature to discuss other ramifications of cockpit feel dynamics. Two exceptions to this are found in the work of Bartel (2003) and McElhone(2004). Bartel studied the dynamics of a feel system with and without nonlinearities and found that the nonlinearities can produce limit cycle behaviour in the feel system itself. McElhone coupled a feel system to an aircraft model and demonstrated the possibility of Pilot Induced Oscillations due to these effects. Neither of these was done for transport airplanes with their systems.

Given a continuous lack of research funding, ultimately, Gibson and Hess (1997) summed it up nicely:

> "As often in the past, shortcomings in these [force-feel] systems will be overcome by the adaptive human pilot, and where this is not possible, the systems will be subject to *a-posteriori, ad-hoc* modifications and improvements." (p. 110)

3.7.3 Summary of Cockpit Feel Characteristics

The origins of feel systems has been seen to be the increase in airplane size and speed: humans could no longer generate the forces required to physically move control surfaces of large size or at high dynamic pressures. While there have been requirements placed on force feel characteristics, these have been shown to be general in nature, and primarily aimed at limiting maxima and minima. No advice could be found for specific design criteria to achieve optimum force or deflection characteristics.

Physical implementation always generates some nonlinearities in the characteristics. These have been shown to be both necessary and to a certain extent desirable. At the same time, these nonlinear features have been seen to generate challenges both statically and dynamically. These have been indicated in the literature, but no comprehensive study has been undertaken. One attempt at categorizing the linearity of feel systems has been evaluated and found to be limited in application.

3.8 Human Pilot Dynamics

Human pilot dynamics have been studied for decades, and the literature is voluminous. The research is found principally in two forms: the psychologists doing their work based on time-and-motion studies, and the control theoreticians working with control system-like models.

The psychologists are well represented with summaries by Jagacinski and Flach (2003), Wickens and Holland (1999), and more recently, a well-funded NASA effort building 4 tools summarized in Foyle and Hooey (2008).

The volume of control-theoretic work is huge, centred around Duane McRuer and his colleagues at Systems Technology, Inc., around Ron Hess at University of California, Davis, and a fast-rising group of very well funded and well organized researchers at Delft University. McRuer's work runs from the first crossover models through the precision models and the structural models, with practical applications of each for a period spanning more than 50 years. Hess's work has concentrated on applications of structural models for handling qualities prediction, while Delft has been focused on the details of precision models, now with the most sophisticated neuro-muscular models available.

Despite a huge volume of work, none has been found to illuminate the pilots' interaction with the feel system for a large transport airplane. Nevertheless, McRuer's notion of modelling a pilot as an element in a control loop is powerful, and can be applied to the subject of feel system interaction of large aircraft with wheel/column controllers.

3.9 Pilot Induced Oscillations (PIO)

Probably the single most confounding problem in flight dynamics is the Pilot Induced Oscillation, or PIO. The phenomenon has been present in airplanes since the very earliest controlled manned flights, and despite having been studied intensively over the past three decades, has appeared in every new transport airplane developed in that time, and some older ones as well. The closed loop oscillation manifests itself as a dynamic instability while the pilot is trying to control the airplane. While amplitudes might vary from a small nuisance to large and destructive (Gray, 2004), the phenomenon is the same: the airplane exhibits motion which the pilot does not intend to command. This instability is sometimes thought of as being akin to the instability of flutter, but more difficult to pinpoint and more insidious, because while flutter has its origins in the interaction between aerodynamics and structural dynamics, PIO has its origins in the interaction between the airplane dynamics and the pilot. While its roots are in the *interaction* between the airplane dynamics and the pilot it is critical to remember that the roots of the phenomenon do not lie with the pilot; they lie with the airplane and its control system. Gibson has succinctly pointed out (1999)

> "The serious handling difficulties found in many fly by wire aircraft were caused by artefacts introduced by the control law designers…The necessary condition for high order PIO to occur is simply stated: the response dynamics permit it. This simple statement is confirmed by its corollary: such PIO is preventable by the provision of easily defined response dynamics that do not permit it."

Considered this way, if the airplane is experiencing commanded motion while the pilot is not intending to command that motion, the airplane can be thought of as being out of control. Consider also that Cooper and Harper (1984) found it necessary to state not once but twice in their paper that even though a pilot might get desired performance, it is *not acceptable* to encounter a PIO on the way to that desired performance.

Similarly, Hodgkinson (1998) suggests both a broad definition and a source by the summary statement:

> “In general, however, most recent efforts have treated PIO as a limiting phenomenon which can occur whenever certain flying qualities rules or criteria are violated.” (p. 126)

Pilot induced oscillations have occurred in transport airplanes in every axis, in all flight phases, between the pilot and the automated system, and Schuler (1986) even describes a recorded transport category PIO involving two pilots. Ilupotaife (1997) and Ilupotaife, Svoboda, and Bailey (1996) have provided a glimpse of PIOs in pitch and in roll for a large jet transport aircraft with a center stick, examples of which are reproduced in Figure 3.19.

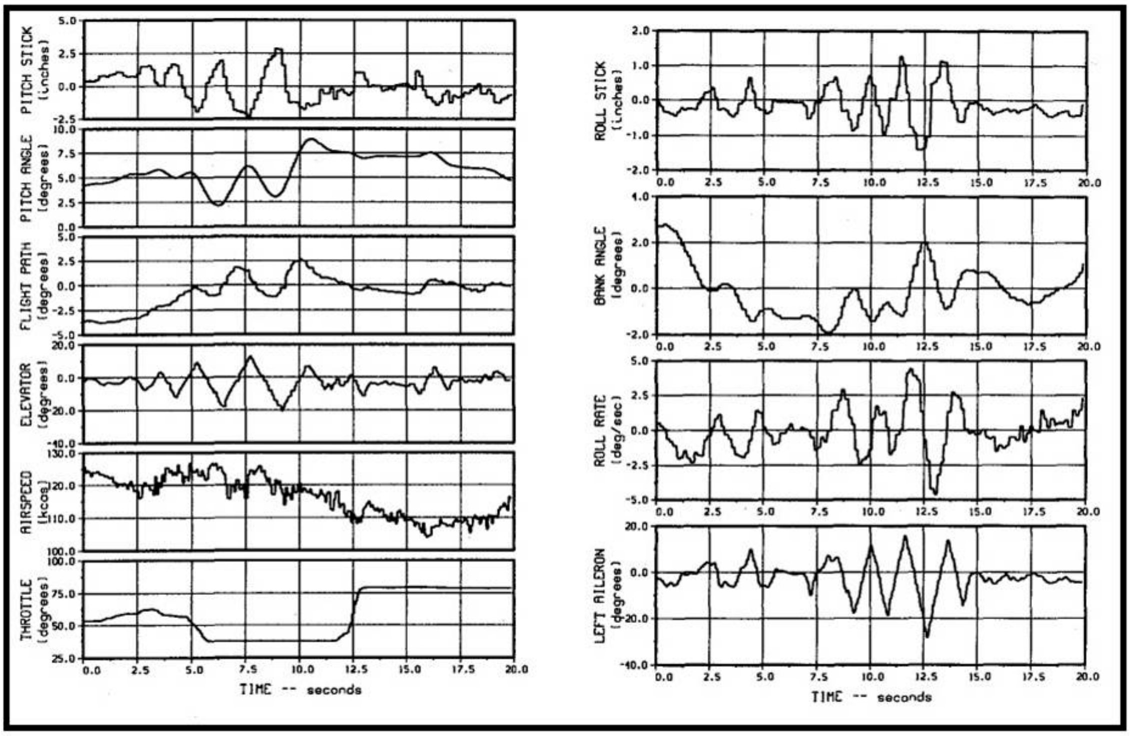

Figure 3-19 Examples of Large Jet Transport PIOs.

Pitch on the Left; Roll on the Right.
(Ilupotaife, 1997; and Ilupotaife, Svoboda, and Bailey, 1996)

Instances of many cycles of oscillation have been observed in the roll axis on transports with sidestick controllers, illustrated in Figure 3-20, from National Research Council (1997).

This implication of flying qualities criteria being violated, resulting in PIO is really bad news for managers on a development program, primarily because it is so hard to identify causes and implement fixes. Hoh (1990) and Hoh and Mitchell (1996) echo this sentiment and discuss the detailed scenario which frequently generates this result.

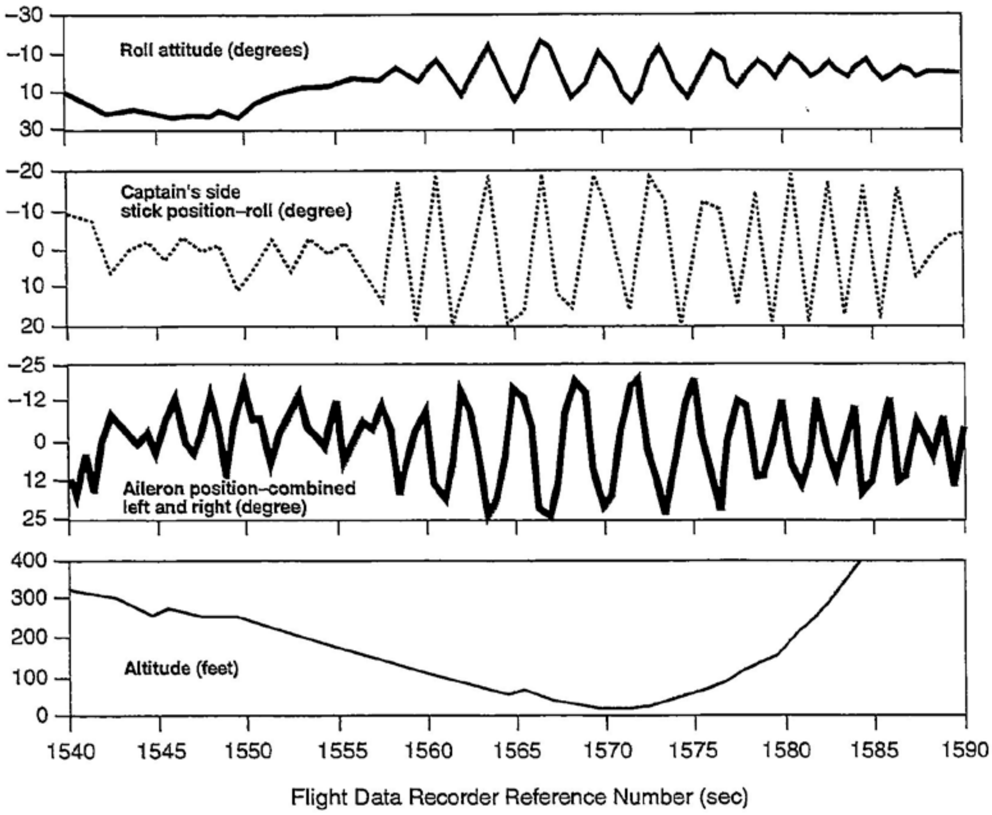

Figure 3-20. Roll Axis Sustained PIO
(From National Research Council, 1997)

In the commercial transport world, attention was really focused on pilot induced oscillations following the China Eastern MD-11 accident (NTSB, 1993) in 1993. This accident not only got significant amounts of attention, but kicked off considerable research efforts among industry and government laboratories. Prior to this event, for commercial transports, PIO was considered a minor subset of Handling Qualities, and some considered that commercial transports could not generate PIO's because their size and inertia did not allow high enough frequencies. Following this incident, and largely as a result of the lessons learned via the huge research efforts which followed, the dynamic interaction between pilots and airplanes has emerged as a dedicated specialty discipline within Airplane Handling Qualities. At this time, the first generation of commercial fly-by-wire transports had just recently emerged and it seemed rather suddenly, the whole industry was concerned.

So great was the concern that the National Research Council (NRC) in the US convened a special committee chaired by Duane McRuer to investigate the problem (1997). The work of this committee highlighted the issue, detailed many of the constituent elements which needed to be looked after, and pointed out fundamental processes and connections in an authoritative and very public way which could not be hidden away in a research closet. It also set the stage – specified the conventions – for much of the work which followed.

What's in a name?

For decades, the phenomenon was known as Pilot Induced Oscillation (PIO) and its meaning was widely recognized. At an AGARD workshop on PIO in 1995, Ralph A'Harrah (1995), then of NASA Headquarters, coined the term "Airplane-Pilot Coupling (A-PC) as a way to direct attention away from the pilot as the cause of the event. According to Hodgkinson (1998), the instability then became referred to as "Adverse Airplane-Pilot Coupling, (still APC). With publication of the NRC report (National Research Council, 1997), this re-naming of the phenomenon to Airplane-Pilot Coupling (APC) was reinforced and this is the reference used in the NRC report. This was done for two reasons:

1) The former term, Pilot Induced Oscillation tended to place semantic "blame" for the events on the pilot, suggesting that it is "induced" by the pilot, when in fact, it is a result of the *interaction* between the pilot and the airplane, and usually the result of poor airplane characteristics, in agreement with A'Harrah; and
2) The use of the term "oscillation" precluded the possibility that there might be an instance of adverse interaction between pilot and airplane which is not oscillatory in nature, but rather aperiodic, (even though one has never been recorded)

The commercial regulatory authorities, FAA in the US and (then) JAA in Europe quickly adopted the new terminology. The rest of the industry, though, struggled with this change for several years, wanting to go back to the familiar PIO nomenclature, but not wanting to discredit the thoughtful work that went into the change in the first place. During this period, several alternates were considered, including: Pilot-In-the-loop Oscillation and Pilot Involved Oscillation (Field, von Klein, van der Weerd, and Bennani, 2000). To add confusion to this, there arose at about the same time a colloquial alternate use of the term Airplane-Pilot Coupling (APC) within the Flight Test office at Boeing, Seattle, describing a different kind of event (to be discussed in detail below). In the end, the industry came to the consensus that pilot's egos were not really that fragile after all, that the industry had never seen an aperiodic event of this nature, and that everyone was confused by the APC nomenclature, so a sort of collective decision was reached to return to the familiar PIO.

The Definition of PIO: just what is it?

The classic definition of the phenomenon was penned by Duane McRuer (in NRC, 1997) defining APC:

> "Unfavourable aircraft-pilot coupling (APC) events are rare, unexpected, and unintended excursions in aircraft attitude and flight path caused by anomalous interactions between the aircraft and the pilot. The temporal pattern of these pilot-vehicle system (PVS) excursions can be oscillatory or divergent (non-oscillatory). The pilot's interactions with the aircraft can form either a closed-loop or open-loop system, depending on whether or not the pilot's responses are tightly coupled to the aircraft response. When the dynamics of the aircraft (including the flight control system [FCS]) and the dynamics of the pilot combine to produce an unstable PVS, the result is called an APC event."

John Gibson (Gibson, 1986) refers to:

> “High order PIO is a continuous out of control attitude instability, the amplitude ranging from small to large and potentially destructive.”

John goes on to distinguish this from what he calls low-order PIO, which is distinguished by discontinuous bobbling or pulsing of the controls. Contrasted to the high-order PIO, in the low-order case, John says that “although the aircraft is not under complete control, it is not out of control” (Gibson, 1999). This notion of the pilot being “in control” is a very important, if subtle, distinction.

The US military specification for Flying Qualities (US Department of Defense, 1997), offers “sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft”, and goes on to describe the phenomenon in the Background Information and Users Guide (BIUG) by referring to “instabilities in the closed-loop pilot/aircraft system”. Pavel, Yilmaz, Smaili, Desyatnik, and Jones (2010) suggest the addition of the term “unintentional” just ahead of “sustained…” in the definition in order to distinguish this phenomenon from one of intentional oscillatory response.

The FAA has chosen to follow guidance provided them by the late Mike Parrag of Calspan by referring to PIO in the context of a broad continuum of motions being “manifested by unintended airplane motions, oscillations, oscillations with divergence, and uncontrollable motions which originate from anomalous interactions between the airplane and the pilot…” beginning with AC25-7A and repeated in Issue Papers generated for every certification program since. (Arnold, 2009) These notions in turn had their origins in a series of short courses generated at the request of the FAA, presenting the collected experience of Calspan staff.

[In Europe, just before the dissolution of JAA and the subsequent rise of EASA, the issues surrounding PIO from a certification standpoint were the subject of considerable harmonization efforts. In the end (facilitated by the necessary budget crisis resulting from the largely un-formed EASA structure) the (then) JAA Flight Test Guide was published with the section on PIO evaluations left

“Reserved”. The singular remaining unresolved issue was the rating method for finding compliance: FAA preferred their Handling Qualities Rating Method (HQRM), which the JAA representatives would not accept, choosing instead to place greater reliance on the independence of their evaluation pilots’ subjective capabilities.]

Many in industry choose to define PIO in terms of specification of the details of the motion, discussed below. In an attempt to summarize these opinions, Mitchell and Klyde (2006, 2008) list no fewer than 8 definitions gleaned from definitions in (Mitchell and Hoh, 2000). They then summarized those definitions into one statement:

> “PIO is a sustained or uncontrollable unintentional[††] oscillation in which the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 degrees out of phase with the pilot’s control inputs, and in which the amplitude of pilot control inputs, aircraft response, or both, is large enough to be intrusive on normal flying.” (Mitchell and Klyde, 2008)

Categorization

Various categories of PIO originated with McRuer (1995). In discussing the then-known PIO events, McRuer proposed several categorization schemes. In the first, he evaluated the outward manifestation of the events. Then in terms of the pilot behavioral dynamics. It is this latter classification which got codified in the NRC report (NRC 1997): Category I is linear; Category II is nonlinear, characterized by rate limiting; Category III is nonlinear, characterized by mode switching or some other large event.

To these, was added a Category IV PIO by Mitchell (2004), as a result of consultation with this author and his experience with large transport category aircraft. “Category IV” PIO describes an adverse interaction between the pilot

[††] See Pavel, Yilmaz, Smaili, Desyatnic and Jones (2010) for a description of the addition of “unintentional”.

and the airplane which involves a structural dynamic response at frequencies higher than the rigid-body PIO frequency. Subsequent to this, a colloquial use of the term “APC” to describe this kind of structural dynamic coupling event grew in the Flight Test office at Boeing Seattle. The rationale for using a different term for this phenomenon includes a recognition of the fact that in the classical (Categories 1-3) PIO, the oscillatory instability arises from the pilot in the loop trying to actively control the motion being generated by those actions. In the Category IV PIO (colloquially called “APC”), the pilot is indeed involved, gripping the control inceptor, but the oscillatory instability is at a sufficiently high frequency that the pilot is not actively trying command motion at that frequency. The pilot is “along for the ride” in the oscillatory motion, which is typically superimposed on a lower-frequency rigid-body commanded motion. The pilot can stop the high-frequency oscillatory motion by releasing the control or in some cases tightening the muscles (attempting to freeze the control) to add damping, so the pilot is indeed driving the motion but the pilot is not actively trying to command motion at that frequency. Finally, colleagues in Russia have referred to this particular phenomenon (Category IV PIO or “APC”) as a “Pilot Assisted Oscillation”

PIO prediction metrics

A number of PIO prediction metrics have appeared over the years. These are summarized nicely by van der Weerd (2000). Critical evaluations have been carried out by Mitchell and Klyde (1998). Probably the most thorough review of all the PIO metrics is Mitchell and Hoh (2000).

Perhaps the best-vetted is the Bandwidth-Phase Delay parameter, useful in both pitch and roll. Bandwidth-Phase Delay as a predictor of Handling Qualities originated in Hoh (1982). Hoh’s definition of Bandwidth is a bit different from the classic textbook definition of the same term. For the purpose of evaluating airplane handling qualities (and PIO), Hoh’s definition is given in Figure 3-21.

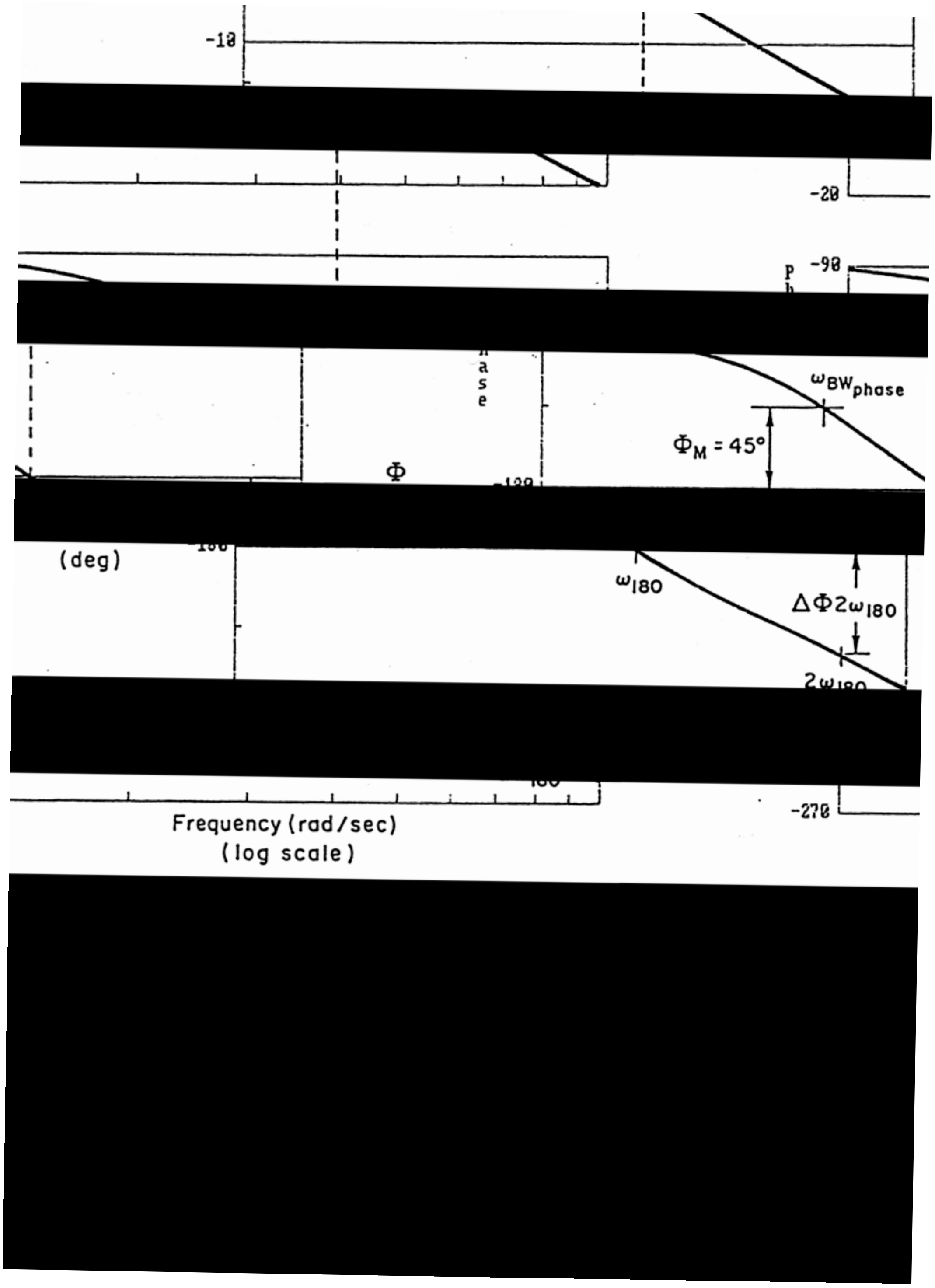

Figure 3-21 Bandwidth – Phase Delay Definitions

In this context, “Bandwidth” for classical control response types is defined as the lesser of 1) the frequency at which the airplane gets to an open loop phase angle of -135 deg., and 2) the frequency at which the airplane has 6 dB gain margin. In practice, this author has never seen a transport airplane which is gain-limited. The phase delay is defined as the difference in phase between ω_{180} and twice that frequency, expressed in seconds, and referenced to the $2\omega_{180}$ frequency. This criterion has its roots in control-theoretic view of airplane control. The bandwidth represents the highest frequency at which the pilot can control the airplane without any pilot-supplied compensation. The boundaries represent iso-pilot opinion lines for a variety of tasks. The phase delay parameter recognizes that if a pilot wants to achieve higher performance and retain closed loop stability, the pilot has the ability to supply lead compensation to stabilize the pilot-airplane combination. The phase delay as defined, represents the slope of the phase roll-off after the -180 degree crossing and recognizes that if the airplane's phase is rolling off fast enough, the pilot will be unable to supply lead fast enough to stabilize the system.

More recently, the Bandwidth – Phase Delay parameter has been used as a measure of PIO propensity (Mitchell and Hoh, 2000). Longitudinal recommendations for Bandwidth – Phase Delay boundaries for PIO are shown in Figures 3-22

At the same AGARD meeting in 1982 which saw the introduction of the Bandwidth-Phase Delay parameter, John Gibson first presented his guidelines (Gibson, 1982). According to Gibson (2000), the necessary elements in order to avoid PIO include the frequency at the -180 degree phase crossing, the average phase rate at the -180 degree phase crossing, and the gain at the -180 degree phase crossing. Gibson's criteria are shown in Figure 3-23. Gibson (2000) points out that while his "average phase rate" is identical to Hoh's phase delay measure, the addition of the -180 degree crossing frequency and the gain at -180 crossing are also important.

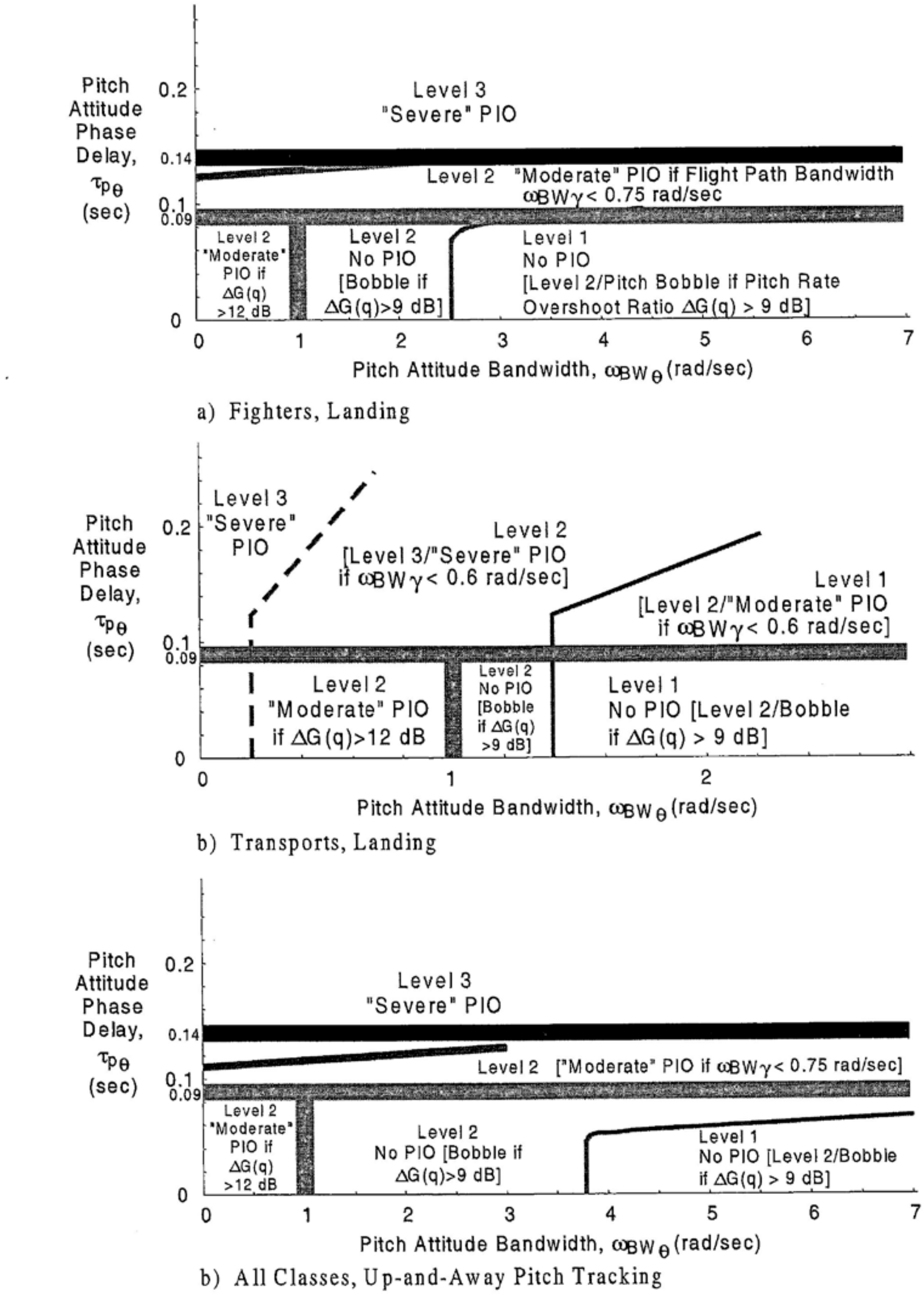

Figure 3-22. Bandwidth-Phase Delay PIO Metric.

Importantly in the context of large commercial transport airplanes, it is not uncommon to find that the frequency at which the airplane crosses -180 degrees is below Gibson's Level 1 boundary. This is simply due to the large size/high inertia character of large transports. Similarly, many large transports are challenged to achieve a Bandwidth of 1 rad/sec, for the same reason. Also, it is interesting to note that Hoh's PIO boundaries are plotted along with the Bandwidth boundaries for Handling Qualities.

Comparison of the boundaries suggests that large transports might well be rated Level 1 for PIO (No PIO), but exhibit Level 2 handling qualities.

Gibson's addition of a gain metric is significant, and illustrates a dimension that Hoh's Bandwidth does not discriminate.

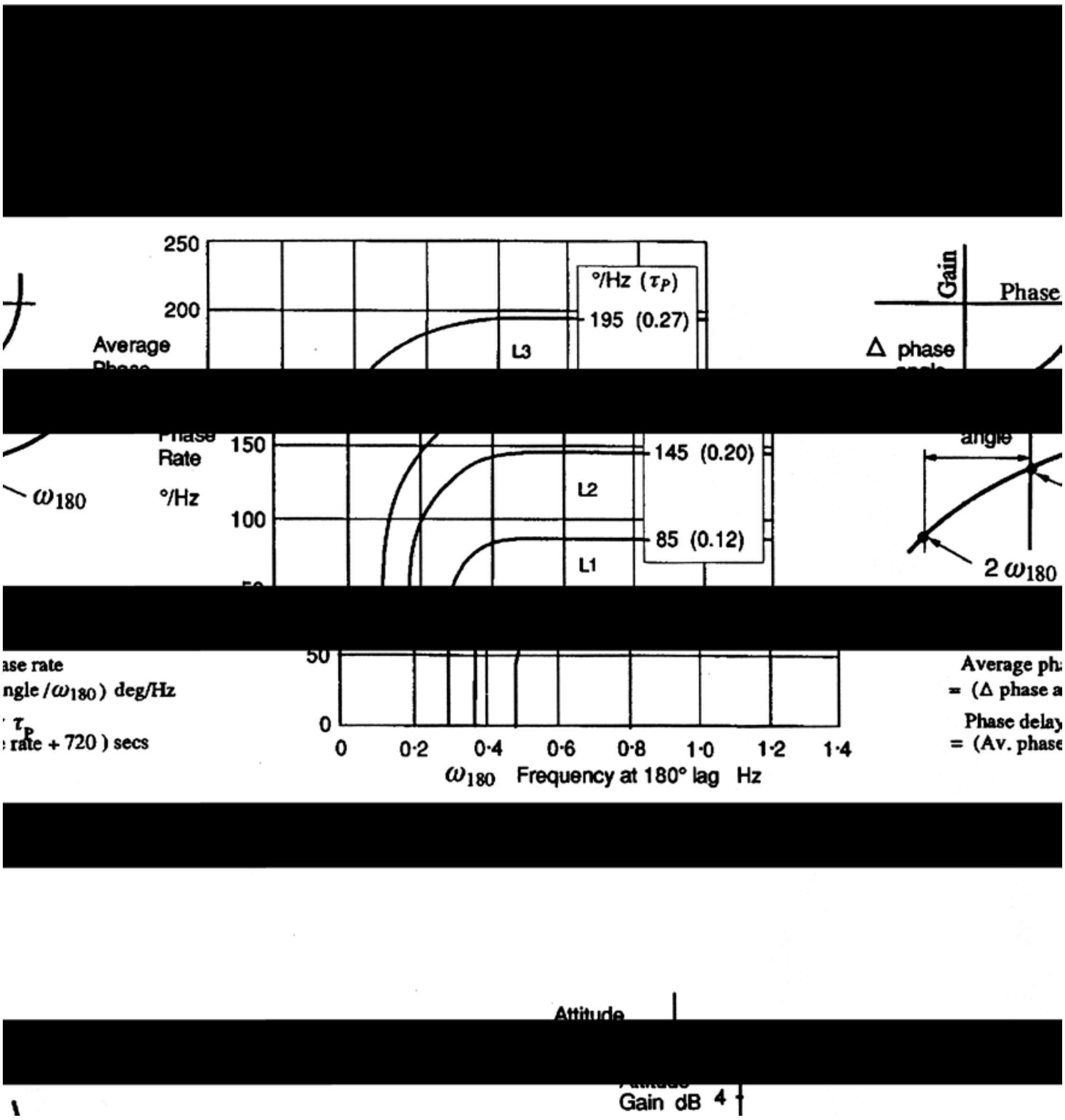

Figure 3-23 Gibson's PIO Crieria

Both Bandwidth and Gibson, though, concentrate their phase measures on the region beyond that for -180 degrees of phase. In one sense, it could be said that at that point, the PIO has already occurred. Neither of these two metrics identify characteristics prior to ω_{180} which could signal a propensity for the pilot to end up in the instability.

3.10 Summary

It has been shown that the equations which describe the motion of aircraft are well known and well understood. For many conditions, the linearized equations can reveal details about the fundamental modes of operation, and, further, these modes can be computed quite rapidly. For the purpose of this thesis, the important reason for understanding these reduced form solution is not the details of frequency and damping for each flight condition. Rather, it is to show quickly how these modes change as a result of *airplane size*.

The requirements on airplane dynamics for civilian aircraft were seen to have stemmed from a differing philosophy than those for military aircraft, and as a result, the civilian requirements are largely qualitative, while the military requirements are heavily quantitative. These are linked, though, via the evaluation process of Cooper and Harper and the notion that the point of having requirements in the first place is to ensure safety (as well as mission effectiveness).

The effect of airplane size on both the resulting dynamics and on the observed response of human pilots in dealing with the dynamics has been recorded, but the significance of either has not been acknowledged. That is, how to compute the dynamics is well known, and pilots have been observed trying to deal with it, but the literature does not address the linkage between the two directly.

There is acknowledged a large economic benefit to configuring especially large transport aircraft with relaxed static stability. While this has been pursued by the industry for a number of years, the emphasis has been primarily on developing robust, reliable augmentation systems to restore the effective stability. What appears to have been missed is an understanding of the details of how the character of the motion changes in the presence of relaxed stability.

While the quasi-steady aerodynamic assumption has enjoyed a long life in the world of flight dynamics, and the role of unsteady aerodynamics has been usefully employed in dynamics loads computations, Hancock (1980) has pointed out that those worlds do not often come together. It has been seen that as airplane size increases, the role of unsteady aerodynamics should become more important to the flight dynamicist. This has not been addressed in the literature.

The link between a pilot and the aircraft is, particularly in large transport aircraft via the control system which typically employs hydraulic actuators to move the surfaces. This was shown to be necessary from a force-generation point of view, but the literature discussing the actuator models themselves tends to encourage simplification to low-order forms. The implications of these simplifying assumptions are not discussed in the literature.

The replacing of the link between the aerodynamic surfaces and the pilot's controller with a control system and hydraulic actuators has been seen to be necessary as airplane size and performance have grown, but with that comes a new need to define the force characteristics for the controller. While getting it wrong has been seen to have catastrophic consequences, there is very little in the way of detailed advice on how to get it right.

It was shown that nonlinear characteristics are necessary, sometimes even desirable in feel characteristics, but attempts to quantify the effects have fallen short. Hess's Linearity Index is one of those attempts and has been analyzed.

While pilot modelling techniques (and associated identification techniques from time series data) have been developed and used for decades, none could be located which would illuminate the subject of a pilot's interaction with the feel system of a transport aircraft with a wheel controller. There are, however, techniques which can be borrowed and applied to the subject of interest.

Pilot Induced Oscillations has been a significant consideration for handling qualities for a long time, and has resulted in accidents. Debate has raged over precisely how to define it, how to test for it, as well has how to design for it's elimination. The most popular (and best vetted) criteria have been reviewed and found to capture significant features which contribute to the phenomenon, but both offer only advice regarding the frequency range above the -180 degree crossing.

This thesis research touches each of these diverse subjects to both extend the state of the art and to illustrate how they all play together in the handling qualities of the airplane.

Figure 3-24 B787 Another Routine Takeoff.

The first group of newly-certificated 787 customer pilots depart Boeing Field for their first experience in the airplane (as opposed to the simulator, where their training took place): airwork and takeoffs and landings at Moses Lake, Washington. Photo Courtesy of Boeing.

4 Large Airplane Dynamics and Pilot Interaction

> We are able now to control complex, powerful, large flexible and widely autonomous systems to extremely high accuracy. We know much more about the mathematical models of our systems and components and are using computational tools to an extent that could become a danger in itself, if we forget to question over and over again their validity for our present design work. A number of spectacular failures have given testimony that the old rule is still true: "Don't model what you cannot test and don't rely on what you cannot verify".
>
> Eveline Gottzein[*]

> "Essentially all models are wrong, but some are useful."
>
> George Box[†]

4.1 Flight Dynamics and Modelling for Large Aircraft

4.1.1 Rigid-Body Modal Dynamics

Considering the results from Chapter 3 regarding the frequencies of dominant modes as airplane size increases in terms of the historical context presented in Chapter 2 produces some interesting conclusions: Lanchester "saw" the phugoid, and analyzed it, but did not know about the existence of the short period. Perhaps it was so fast that he could not see it.

Gough at NACA first began complaining about the short period oscillation when the airplane on which he found it encountered a rut in the runway. The airplane weighed about 17000 pounds. Perhaps this was the first time (when anyone was looking for dynamic characteristics) that they encountered one slow enough to see. In the 1940's and beyond, airplane weights and speeds grew dramatically, and the research focused not on how to suppress that annoying short period mode, but on how to take advantage of those characteristics, now that they were slow enough to make use of, and not be just annoying.

[*] Borrowed from the History of the International Federation of Automatic Control (IFAC) Technical Committee on Aerospace. Gottzein was the chair of the Aerospace Technical Committee from 1976-1987, again from 1996-1999 and authored the inaugural edition of the committee's history. (Gottzein, 2007).
[†] George Box is an economist accustomed to working with models to represent systems. [Box, 1987]

As transport aircraft have continued to grow in size and inertia, the modal dynamics presented to the pilot have changed as well. It was seen in Chapter 3 that while phugoid frequencies are relatively constant across airplane sizes (for similar airspeeds), the short period mode gets slower. Computing the modes is not an issue, as the methods are well known, but knowing what to do with a short period which is, say, 8-10 seconds long is more difficult.

The first step is acknowledgement. Many simply have not thought about the issue, but most are surprised to hear that it is that slow.

A second consideration is that as the short period gets slower, it gets closer to the phugoid mode. One side-effect of this is that the modal approximations lose validity, but this is of little consequence, since it is relatively easy to compute the exact solution. More important is the effect that it has on the human pilot trying to control both modes (and do other things) at the same time. It was seen that human pilots tend towards techniques more often seen as "supervisory control" as the dynamic modes slow down: resorting to pulse-like behaviour.

The minimum short period natural frequency in Appendix A is 0.7 rad/sec, or a period of 8.97 seconds. Even with natural stability, the large airplane push this boundary, yet we do not hear of significant complaints about inadequate handling. It is probable that pilots adapt as best they can, and performance degrades. This was seen in the large airplane in-flight simulations of Weingarten and Chalk (1981) in which the pilot were seen to reduce their level of aggressiveness simply because they were told they were flying a large airplane. The background information in the US Mil-Hdbk (US Department of Defense, 1997) points out:

> "In our opinion the fact that the handling qualities of these aircraft are satisfactory is mainly the result of an adapted piloting technique. The pilots have learned to cope with low short period frequency, low acceleration sensitivity and large time delays by avoiding to get into the control loop. Pilots flying aircraft like B747, DC-10, and C5 will tell you that, e.g. the landing flare is an open loop manoeuvre." (p. 201)

In evaluating classical airplane dynamics, the phugoid mode is given little attention, as pilots usually have no difficulty controlling it, and in fact usually do it without thinking much about it (Cook, 2007). It is important to remember that this observation is made on airplanes with significant frequency separation between the short period (actually, the pitch attitude numerator) and the phugoid mode. It seems easy to say that the pilot should be able to control the phugoid when the pilot has access to a high-frequency controller. When the airplane gets large and the short period mode gets close to the phugoid, it is not quite so obvious.

These represent areas in which additional research is clearly required.

4.1.2 Transient Dynamics

In a reprise of the ubiquitous second order system discussed in Chapter 3, it is interesting to note that most authors in these discussions, look at the second order solution, primarily by looking at the transient only (e.g. by setting the forcing function to zero, or by looking only at impulse responses, or step or ramp responses), or by looking at responses to sinusoidal inputs only (leading to frequency response analysis). Very little discussion takes place in between, except the occasional reference to brute-force time-marching simulation routines. There may be good reason for this: McRuer, Ashkenas, and Graham point out:

> "...the transfer function could, in principle, be measured from the responses to various $e^{s_1 t}$ input forms to the extent that the forced response can be separated from the transients represented by the summation. Ordinarily, this is frustratingly difficult or practically impossible. However, for stable or just slightly unstable systems the separation is readily accomplished for the special case of s=jω. Then the forced response is a sinusoid that is separated from the total response by the simple expedient of waiting for the transients to become insignificant for the stable case, or by subtracting out the slightly divergent mode(s) in the unstable case." (p. 91)

As was seen in Figure 3-3, pilots don't fly using just sinusoids or just steps or ramps with zero initial conditions. The argument could be made that pilots cannot see the spectrum at all. What a pilot "sees" is what the airplane did in the first few seconds after a control input was made. There is also evidence that there are thresholds in what the pilot can see, and what the pilot can remember seeing. Visual perception thresholds have been measured, for example as Figure 4-1, adapted from Efremov, Ogloblin, Predtchensky, and Rodchenko (1992). This data shows the results of experiments in which pilots were shown oscillations in airplane attitude at different frequencies and different amplitudes, and asked to identify when they could first distinguish that the airplane was moving (and they were required to distinguish not just the motion, but to be able to identify the phase of the motion). For example, the data shows that if the aircraft were pitching at 0.1 rad/sec, the pilot could just identify the pitch oscillation when it first got as large as 0.5 deg. At lower frequencies, the amplitude must be larger before the pilot could recognize it. At higher frequencies, the amplitude for recognition did not change much. For roll, the pilot's field of view was found to be important; not so much for pitch and yaw.

These are absolute thresholds, taken in a quiet laboratory environment. Operationally, the requirement would be much larger, as large as 10-15 times larger depending on the task and the workload. In addition there is anecdotal evidence suggesting, for example, when the Dutch roll frequency gets low enough, pilots will report a directional control problem but will not report it as Dutch roll. Presumably this is because they cannot remember the motion long enough to recognize that it is sinusoidal.

Given that pilots don't typically use only steps, ramps, or wait for the transient to go away when they make control inputs to fly airplanes, it is useful to extend the second order solution to include a driving function

The complete solution to the second order problem is given by Gardner and Barnes (1942), and reproduced in Appendix F.

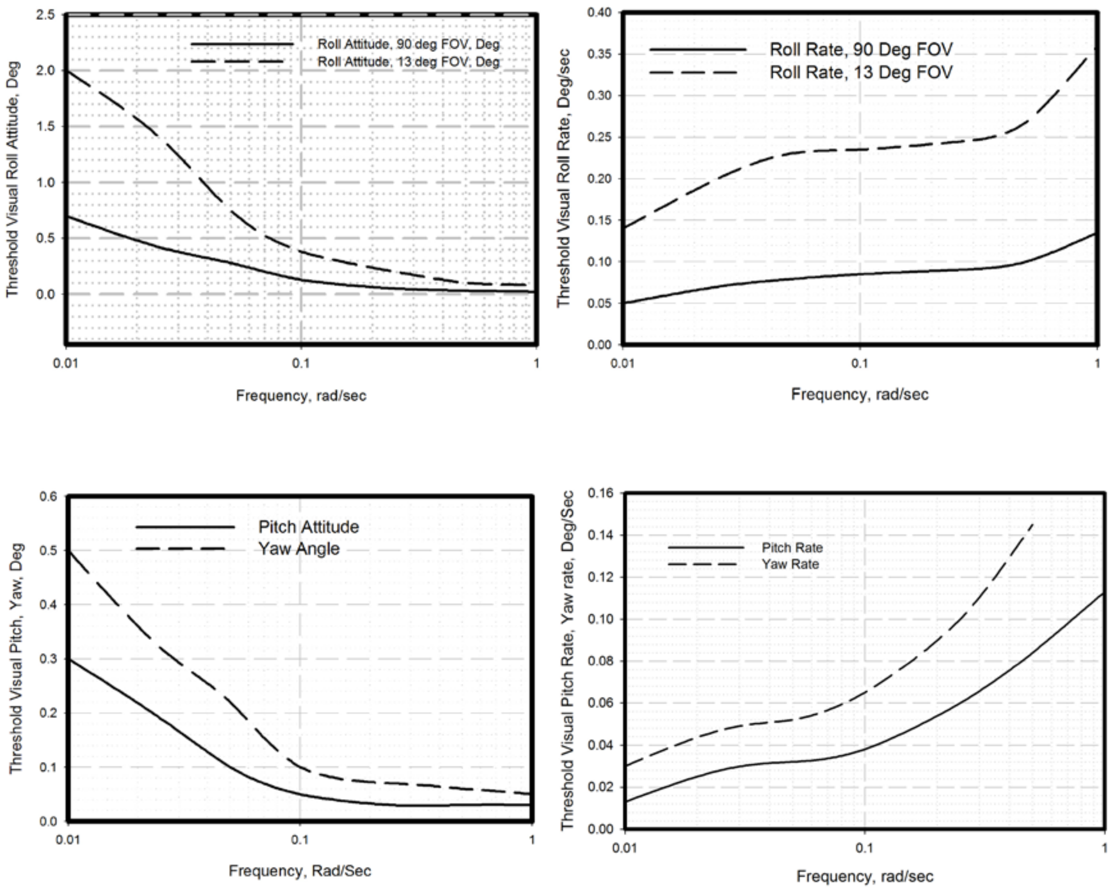

Figure 4-1 Visual Perception Thresholds
(From Efremov, Ogloblin, Predtchensky, and Rodchenko, 1992)

Gardner and Barnes give the solution in terms of the sum of both the transient and of the driving function:

$$y(t) = \frac{F_m}{A\left[(\beta_0^2 - \omega_1^2)^2 + 4\alpha^2\omega_1^2\right]^{1/2}}\cos(\omega_1 t + \psi - \theta) + \frac{1}{A\beta}\left[\frac{m^2 + n^2}{(\beta_0^2 - \omega_1^2)^2 + 4\alpha^2\omega_1^2}\right]^{1/2} e^{-\alpha t}\cos(\beta t + \lambda) \tag{4.1}$$

For $0 \le t$, in which

- $\theta \stackrel{\Delta}{=} \tan^{-1} \dfrac{2\alpha\omega_1}{\beta_0^2 - \omega_1^2}$
- $m \stackrel{\Delta}{=} \beta\left[g + y(0)A(\omega_1^2 - \beta_0^2) - y'(0)B\right]$
- $n \stackrel{\Delta}{=} h\omega_1 - g\alpha + y(0)\alpha A(\omega_1^2 + \beta_0^2) + y'(0)A(\alpha^2 + \omega_1^2 - \beta^2)$, and
- $\lambda \stackrel{\Delta}{=} \tan^{-1} \dfrac{-n}{m} - \tan^{-1} \dfrac{-2\alpha\beta}{\alpha^2 + \omega_1^2 - \beta^2}$

Now the first term in (4.1) is the steady-state portion of the response, having the same sinusoidal waveform and the same frequency as the driving function. The second term in (4.1) is the transient portion of the response. It has its origins in the solution of the system characteristic equation. The damping constant α is given by the magnitude of the real portion of the poles. The time constant is the reciprocal of the damping constant. The characteristic angular frequency β is the magnitude of the imaginary part of the poles. Gardner and Barnes (1942) point out that both α and β depend

> "*solely* on the constants of the physical system and the system's interconnection, and are *independent of its excitation*". (p. 173) (emphasis added)

While the *character* of the transient is determined by the locations of the system poles, the *amplitude* is determined by the initial conditions and the initial phase of the driving function. This can be seen in the parameters m and n. It is clear that selection of these conditions can generate a transient term of appreciable size compared with the steady-state solution. Moreover, since the frequencies of the two terms which make up the total solution are different, the total solution may appear chaotic. Gardner and Barnes point out that even with zero initial conditions, there will always be a transient evident in the total solution, since there is no value of ψ which makes both m and n zero.

The solution expressed in this form makes the nature of the total airplane response clear: the "steady-state response", as reflected, e.g. in Bode form is an oscillation at the driving frequency, while the frequency of the transient response depends only on the location of the roots of the characteristics equation.

In order to help the time-domain-based pilot, it is necessary to know just how long it will take before the transient goes away. This has been computed and is shown in Figure 4-2.

Figure 4-2. Time to Dissipate a Transient

In order for the transient to go to 10% of it's original amplitude (which was dependent on the specific phasing of the initial conditions), it will take, for a typical short-period damping of ~.4, perhaps ¾ of a cycle. Just how long that is depends on the airplane, but it's not atypical for a large transport to exhibit a short period of 8-10 seconds long. What this means is that anytime the equilibrium is disturbed, the airplane will go through it's transient, and it might take 6 or 7 seconds for that to happen. Putting this in perspective, consider that when a transport is on approach at a normal approach speed on a three degree glideslope, the vertical speed will be in the neighbourhood of 10-12 feet per second. Upon reaching 50 feet above the runway, the pilot will be within 4 seconds of impacting the ground. Now the transient is 6-8 seconds long. This is an important consideration. Certainly, in the tracking task of Figure 3-3, the pilot did not wait until the transient went away, nor did the pilot engage in continuous control inputs.

4.1.3 Relaxed Static Stability

When attention was focused on relaxing static stability in the 1980's the flight dynamics community and the flight controls community focused on recovering dominant mode characteristics: frequency and damping of the "short period". What McRuer pointed out (McRuer and Myers, 1982) is that while they found a mode containing pitch rate which exhibited desired frequency and damping characteristics, it may not be what it appears. Indeed, when the eigenvectors were computed for the case flown by Weingarten and Chalk (1981), which had gotten McRuer's attention, the high frequency oscillatory mode labelled "short period" based on the frequency and damping had constituents which did not look at all like a short period. What they had was a mode which exhibited short-period-like frequency and damping, but it contained significant amounts of speed variation. This was reflected in the pilot comments at the time, but it was not pursued any further.

It is illustrative to examine what happens to the bare airframe characteristic modes as the stability is allowed to relax beyond the stability boundary. Figure 4-3 depicts a locus of roots as the centre of gravity is moved aft for longitudinal characteristic equation which might be taken as typical for a wide-body airliner.

With the centre of gravity several percent forward of the Neutral Point, the roots are shown at position "1". At this condition, there is a distinct oscillatory short period and an oscillatory phugoid, closer to the origin. The characteristics of these modes of motion are given in Table 4-1.

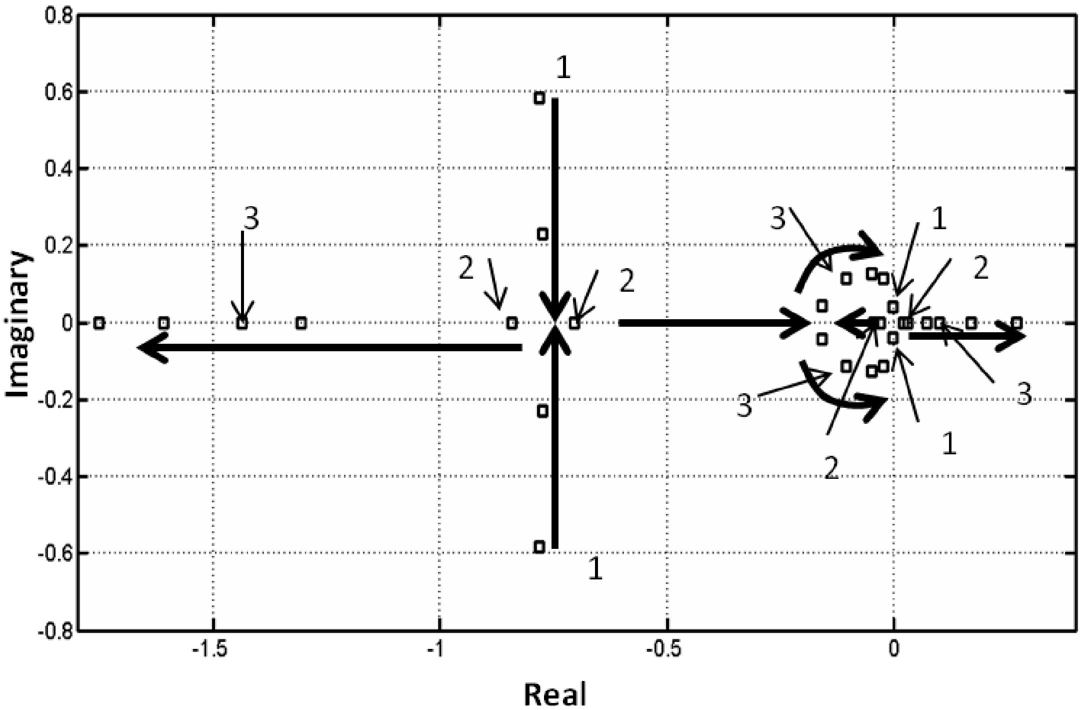

Figure 4-3 Locus of Roots as CG is Moved Aft

Mode	Frequency	Damping	Period
Phugoid	0.038	0.087	162 sec.
Short Period	0.975	0.801	6.44 sec.

Table 4-1 Example Characteristics ahead of Neutral Point
(Centre of Gravity Position 1)

While the eigenvalues provide the frequency and damping of these two oscillatory modes, the eigenvectors provide the details of the motion contributed by each mode and in each state. For this condition, the eigenvectors are given in Table 4-2 in terms of their relative magnitudes and phases. This table and Table 4-1 can be compared to Figure 3-1 to give a more complete picture of the motion which takes place (and the pilot sees). In this case, because the two modes are both oscillatory, roots 1 and 2 are conjugates as are roots 3 and 4.

	Root 1	Root2	Root3	Root4	Motion State
Magnitude	.2248	.2248	.9976	.9976	U
Phase	-77	77	0	0	
Magnitude	.7438	.7438	.0072	.0072	α
Phase	0	0	179	-179	
Magnitude	.4396	.4396	.0027	.0027	q
Phase	91	-91	4	-4	
Magnitude	.4506	.4506	.0695	.0695	θ
Phase	-51	51	-98	98	

Table 4-2. Eigenvectors for Centre of Gravity Position 1

With reference to table 3-1, it is easy to see that the short period mode, which oscillates at a frequency of .975 rad/sec and has a damping of 0.801 is made up of motion from roots 1 and 2, of which the relative speed contribution is approximately .22 compared to the angle of attack variation of .77, pitch rate and pitch attitude of .44 and .45 respectively. Moreover, for this mode's contribution to the motion, relative phasing of the motion between the states is also given: pitch attitude is ~50 degrees away from angle of attack, pitch rate is ~90 degrees away from angle of attack, and speed variation is ~77 degrees away from angle of attack.

Eigenvectors have units, and the difference in units of speed and angles can affect the numerical comparisons. I this case, the speed is in Ft/Sec, while angle of attack and pitch attitude are in degrees and pitch rate is degrees per second. This particular combination of units has been commented by Schmidt (2012) as being closest to being "equal" for the sake of making these comparisons.

The phugoid contributions are made up in the same way: phugoid motion is mostly speed, while the contributions to angle of attack and pitch rate are roughly 3 orders of magnitude smaller, and pitch attitude is a factor of ~20 smaller than the speed variations. In the phasing of this phugoid motion, pitch rate and speed are nearly in phase, angle of attack is nearly 180 degrees out of phase, and pitch angle is nearly 100 degrees out of phase with speed.

This is the motion that the pilot sees, and how he sees it evolving.

The next point of interest on Figure 4-3 is labelled Point 2. This represents a centre of gravity location just aft of the neutral point. In getting to this point from Point 1, the short period roots migrated parallel to the imaginary axis, so the frequency has decreased, while the damping has increased. Once the oscillatory roots meet at the real axis, they split and migrate in different directions along the axis. At this point, they should no longer be referred to as "short period" roots. They are simply first order roots. Similarly, the phugoid roots have met at the real axis and begun to migrate in different directions, with the right-most of those roots crossing into the Right Half Plane (unstable).

It is instructive to see just how the evolution of motion for this location of centre of gravity comes about. The roots, as already mentioned have degenerated into 4 real roots, and the motion will be the combination of 3 subsidences and one aperiodic divergence. With no oscillatory motion, it is inappropriate to speak in terms of frequency and damping. Rather, these modes contribute to "quickness of motion", with the relative quickness given by the location of the real roots. As before, the eigenvectors describe how the motion contributed by each root is distributed among the states. For this case, the description is in Table 4-3.

	Root 1	Root2	Root3	Root4	Motion State
Magnitude	.305	.4672	.9983	.9972	U
Phase	0	180	180	0	
Magnitude	.945	.879	.014	.013	α
Phase	180	0	0	180	
Magnitude	.076	.051	.002	.002	q
Phase	0	0	0	180	
Magnitude	.091	.071	.056	.073	θ
Phase	180	180	180	180	

Table 4-3. Eigenvectors for Centre of Gravity Position 2

This motion is very interesting. The motion generated by the fast-responding stable root is mostly angle of attack and speed, with pitch rate and pitch attitude nearly two orders of magnitude smaller. In addition, speed and pitch rate are 180 degrees out of phase with the evolution of angle of attack and pitch attitude. The second-from-the-left root is very similar to the faster one expect it contains somewhat more speed and somewhat less angle of attack contribution. But the phase angles , which are also binary at 0 or 180 are 180 degrees different for speed and angle of attack from the fastest mode. The third stable root contributes nearly all speed, as does the unstable root, except the two are 180 degrees apart in all states except pitch attitude.

Finally, by point 3 on Figure 4-4, the stable root has gotten more stable, the unstable root has gotten more unstable, and the two in the middle have combined to form a new oscillatory mode, generally referred to as the “third mode”. The motion at this CG is made up of a stable first order response, an unstable first order response, and a stable (for this particular configuration) oscillatory “third mode”. The frequencies and dampings are again given by the eigenvalues, and are presented in Table 4-4:

Mode	Frequency (time constant)	Damping	Period
Unstable Root	(10 seconds)	-1.0	--
Stable Root	(0.7 seconds)	1.0	--
Third Mode	.156 rad/sec	.6	40 seconds

Table 4-4 Example Characteristics Unstable with Third Mode
(Centre of Gravity Position 3)

For this condition, the oscillatory mode is somewhere between where a normal phugoid would be expected (somewhere around 60 seconds) and a normal short period (somewhere around 8-10 seconds). Again, the eigenvectors can provide even more insight, in Table 4-5:

	Root 1	Root2	Root3	Root4	Motion State
Magnitude	.27	.97	.97	.98	U
Phase	0	0	0	180	
Magnitude	.767	.05	.05	.033	α
Phase	180	90	-90	0	
Magnitude	.526	.371	.371	.021	q
Phase	0	90	-90	0	
Magnitude	.366	.238	.238	.206	θ
Phase	180	-45	45	0	

Table 4-5. Eigenvectors for Centre of Gravity Position 3

At this condition the fist root is seen to generate mostly angle of attack and pitch rate with some speed and pitch attitude contributions. Phase angles for speed and pitch rate match, while angle of attack and pitch attitude are 189 degrees away. The oscillatory mode looks much like a phugoid, with significant speed content, some pitch rate and pitch attitude, but nearly no angle of attack. One interesting feature of this condition is that pitch attitude is now 45 degrees away from speed, angle of attack, and pitch rate. The unstable root is comprised nearly all of speed, only a bit of pitch attitude and nearly no pitch rate or angle of attack.

This situation is what Myers, et al (1982) was trying to warn the FAA about when they wrote about superaugmentation. While Myers never looked at the eigenvectors, he did recognize that the oscillatory mode which his system quickened to be referred to as a “short period” did not come from a short period at all, but rather the leftover third mode. This analysis reveals that the content of the modal motion does not look like a short period at all. This also could be the reason why the evaluation pilot in Weingarten and Chalk’s (1981) experiment had difficulty sorting out the speed and pitch attitude for the long aft-tail high pitch rate augmentation configuration which got Myer’s attention in first place.

It is recommended that augmentation design consider the eigenvectors and the consequent modal motion, particularly for slow-moving modes, because they are more visible to the pilot. Further, the topic of sensitivity of handling qualities to eigenvector structure should be evaluated with pilot-in-the-loop studies to understand whether pilots can effectively deal with potentially conflicting cueing environment.

4.1.4 Aerodynamic Force Modelling

One rule of thumb is that if any event occurs in less time than it takes for the wing to move 4 chords downstream, then quasi-static aerodynamics should not be trusted, and more sophisticated unsteady aerodynamic methods should be invoked. What is perhaps not so well understood is what the effect of airplane size has on the perception of what is “fast”.

Large transport aircraft are sized for current runway environment (and slightly larger), so as the size increases, landing speeds are relatively constant. The time to transit a distance equal to four chords has been computed for three different chord lengths across a range of speeds. These comparisons are plotted in Figure 4-4.

If 140 knots is taken as a representative landing speed for these large airplanes, it is clear that this rule of thumb suggests the time for lift to build on the wing surface is on the order of 350 – 700 ms.

Considering that these airplanes have short- and Dutch roll natural periods on the order of 7 to 10 seconds, this 350 – 700 ms might seem small. On the other hand, the requirements of MIL-HDBK-1797 (US Department of Defense, 1997) suggest that the addition of 150 or so milliseconds is enough to deteriorate the handling from Level 1 to Level 3. Clearly, a few hundred milliseconds is significant. The concern here is that use of the quasi-static aerodynamic assumption will produce an optimistic result which the airplane cannot achieve.

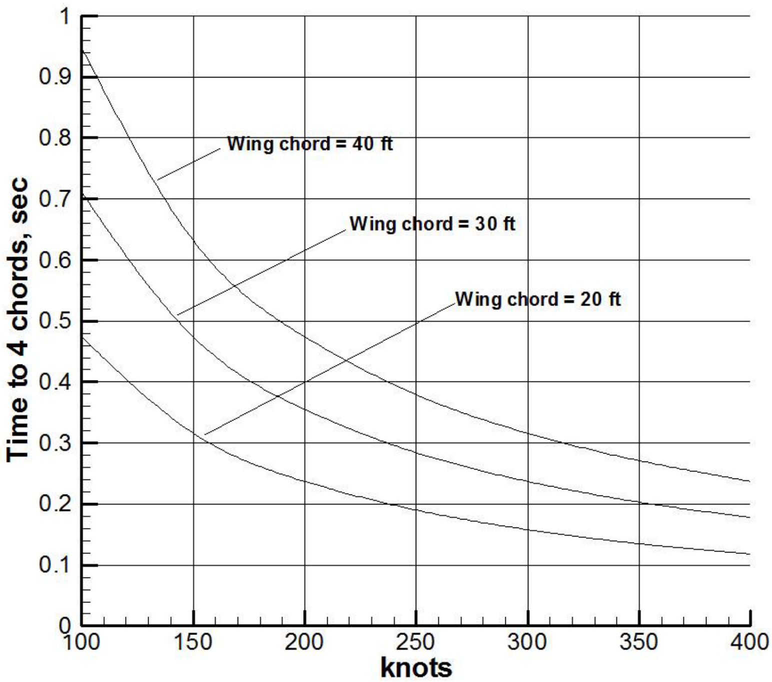

Figure 4-4. Time to Four Chords

In order to get a better understanding of this phenomenon, the detailed unsteady lift of a deflecting aileron has been computed with the help of ESDU

Item 84020, (Engineering Sciences Data Unit 1984). Time domain computations have been generated for wings of 20, 30 and 40 foot chord lengths at 140 knots and at three different aileron deflection rates, corresponding to reaching full deflection in 2.5, 5, and 10 chords, using a 1-cosine deflection form. The 40 foot chord results are plotted in Figure 4-5.

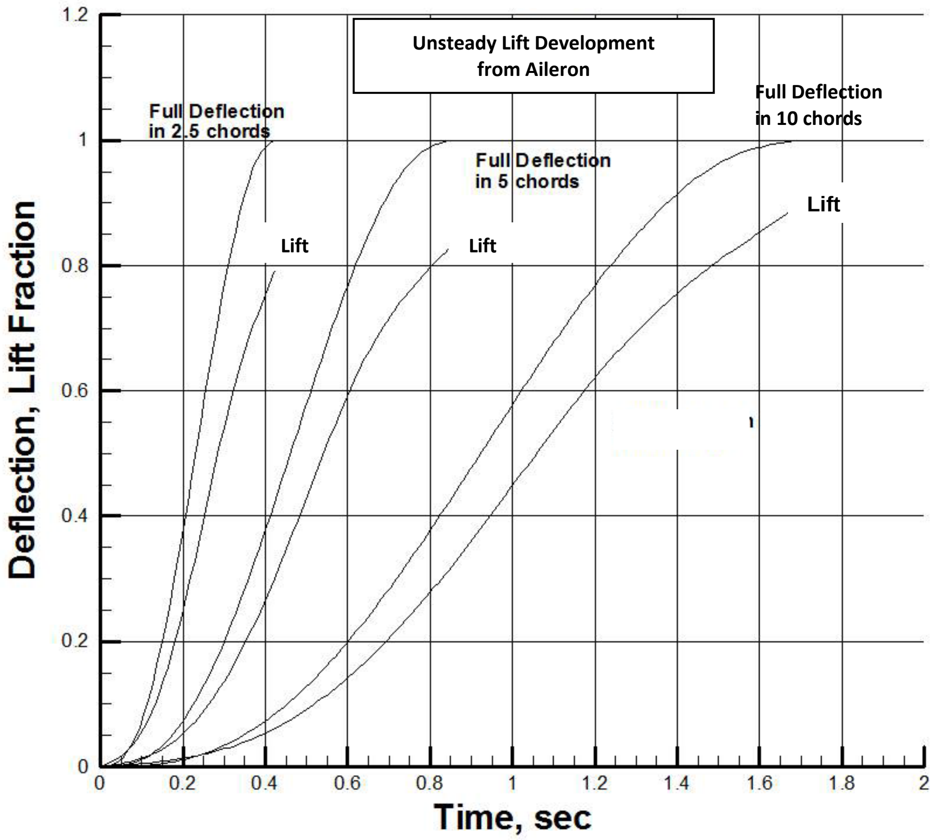

Figure 4-5 Lift Due To Trailing Edge Deflection

On the left side of the figure, the first pair of curves represents the control deflection and the aerodynamic loading respectively for the fastest deflection rate studied. The upper curve indicates the control deflection. By the time the control reaches full deflection, the lift buildup has only reached 80%. Similar results are seen at the moderate deflection rate (in the middle of the figure), corresponding to 5 chords to full deflection.

The surprising result is for the slow deflection. By the time the surface reaches full deflection, the load is only at 90%.

Examination of these three curves gives rise to the realization that the lift buildup corresponding to a given deflection time history looks very much like the response to a second- or higher- order lag function. This realization may give the flight dynamics engineer a straightforward way to account for the unsteady lift buildup during transient manoeuvres: the simple expedient of inserting (for visibility) an additional filter between the control surface actuator and the aerodynamic load presented to the equations of motion.

Examining Figure 4-5 again, but now looking not at lift, but in the other direction at time, the aerodynamic loading always lags the control surface deflection by a significant amount. But it is realized that a lag in a time-varying force curve is very difficult to evaluate, because what is important is the integrated force.

In order to evaluate the lag associated with even a crude approximation, a simple computation was carried out. First, a first over second order filter was fitted to the aerodynamic lift curves of Figure 4-5. While a second-order filter will not capture every detail of a Wagner function of unsteady lift development, it *has* been used to estimate Kunser functions (van der Vaart, (1985), Hancock, (1980), Hancock, (1995)). Second, van der Vaart's approximation to the Wagner function was evaluated for the three chord lengths considered: 20, 30, and 40 feet. This function has the form of a notch filter, as in Equation 4.2:

$$H(s) = \frac{(1+\tau_1 s)(1+\tau_2 s)}{(1+\tau_3 s)(1+\tau_4 s)} \tag{4.2}$$

Where $\tau_1, \tau_2, \tau_3, and\, \tau_4$ are explicit functions of aerodynamic time $\frac{\bar{c}}{2v}$.

This was then inserted upstream of a lateral response transfer function representing a transport airplane and driven by sine waves of various frequencies. For comparison, the same lateral response transfer function was driven by the same sine function without the prefilter. The lag associated with putting the filter on the input (aerodynamic generation) signal was then evaluated by looking at the peaks of the response after the transient had disappeared, as shown in Figure 4-6. In this case, the total effective delay was ~200 ms.at the middle frequency evaluated, as shown in Figure 4.3. In addition, the delayed response had slightly smaller amplitude, as would be expected.

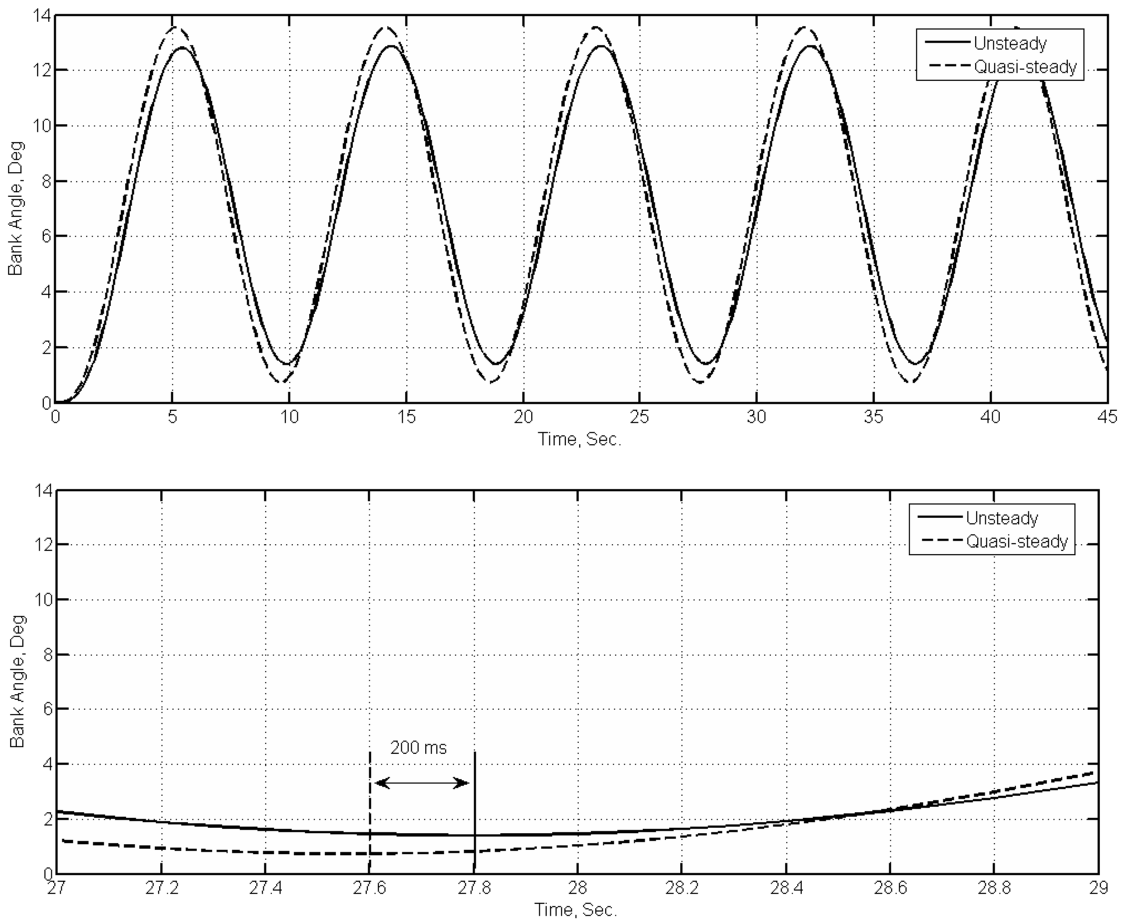

Figure 4-6. Time Response Effect of Simulating Unsteady Aerodynamic Effects.

The intent of this approximation process is less about modelling the nuances of unsteady aero in the time domain as it is about recognizing that there is a lag in the build-up of aerodynamic forces and accommodating some representation of it. The danger of not including some lag function is at least twofold. If the phenomenon is ignored altogether, the performance predictions will likely be non-conservative from the point of view of lag between the pilot and the airplane response. Second, when the response dynamics are measured in flight, if there is not at least a "placekeeper" in the model, any differences will be allocated to other parts of the model, which will likely further confuse any later matching processes.

4.1.5 Actuator Modelling

Two very important characteristics of hydraulic actuators worthy of discussion in the context of airplane handling qualities analysis are the linearity of the performance of the device, and, even for linear characteristics, the form of model used to represent it. First, the analyst needs to understand, and not at a superficial level, that the dynamic response performance of these devices is fundamentally nonlinear in character. Because actuators occupy a position between the flight control system commands and the aerodynamic effectors' production of forces and moments, these nonlinearities or rather, their effects, are critical and need to be understood. Thereafter, a decision should be made whether the nonlinear characteristics will be dealt with explicitly, worked around, e.g. by limiting the scope of the analysis to "linear" regions, or simply ignored.

The second notion of importance is that even for linear assumptions, the form of the linear model chosen is important to the outcome. Models employed should be as simple as is necessary to avoid obscuring understanding of the results with unnecessary detail, while being sophisticated enough to capture the significant elements brought to bear on the problem. Choices regarding the linear form of model employed often generate further limitations on the applicability of the results, and these should be understood.

Once the pilot and/or control system decides that the aerodynamic control surfaces need to move, it is up to the surface actuator to make that happen. The actuator is assumed to follow the command of the pilot and/or control system, and any deviation from that commanded motion is likely to be important to the pilot's ability to precisely control the airplane.

There are at least two significant ways in which hydraulic actuators exhibit nonlinear characteristics which are important in this context. Even though they are both amplitude-dependent characteristics, they should be regarded as two independent “dimensions” or independent sources of contamination of linearity.

The first of these is the relationship between actuator bandwidth and the rate at which the actuator can actually move the surface. Practitioners in the field understand that these two measures of performance are distinct and while they are indeed related, the relationship does not necessarily exist throughout the range of motion of the actuator.

This can be illustrated with a simple example. It would not be uncommon for an actuator to exhibit a bandwidth of, say, 20 radians/second while at the same time, be able to drive its surface from one stop to the other at a rate of, say, 40 degrees/second. The first of these measures is used to determine closed loop stability in the presence of aeroelastic and loading conditions, while the second is used to determine airplane flight dynamics control capability. The fact that these two measures are not necessarily consistent may not be immediately obvious, but can easily be shown.

If the commanded position is defined as a sine function:

$$\delta_{command} = A\sin(\omega t) \tag{4.3}$$

The velocity of the command is then

$$\dot{\delta}_{command} = A\omega\cos(\omega t) \tag{4.4}$$

Clearly, the peak velocity is a function of the amplitude: even at constant frequency, the velocity required to follow a sinusoidal command increases with amplitude of the command. In the nonlinear world, when the actuator can no longer keep up with the velocity commanded, its output becomes limited by its maximum rate. The amplitude at which that happens can easily be seen. The actuator at 20 radians/second reaches its 40 degree/second rate limit at an amplitude of +/- 2 degrees, even though its total travel might be +/- 20 degrees.

The velocity of a hydraulic piston is determined by how quickly the fluid can fill the cavity behind it, and how quickly it can be evacuated ahead of it. This is a function of the system pressure and the size and shapes of the orifices and passages in the actuator and valve. As the amplitude or frequency of the command increase, at some point the valve will be open as far as it can go, and the actuator will be operating as rapidly as it can. When this happens, the actuator is said to be rate limited, and its performance is no longer linear. If this point lies within the range of deflections and commanded velocities available to either the pilot or the control system, the consequences should be evaluated very carefully.

A numerical example from the opposite point of view can be equally illustrative. Consider the same actuator designed to operate at 20 rad/sec at an amplitude of +/- 1 degree of surface deflection. This implies that the actuator can produce peak surface deflection rates of 20 deg/sec. If the surface deflections required are +/- 20 degrees, this actuator is capable of following a stop-to-stop sinusoidal command of only 1 rad/sec. At maximum rates, and ignoring the dynamics of the rate reversals, this actuator could support approximately 1.5 rad/sec stop-to-stop with a triangular response. If it is likely that either the pilot or the control system might demand surface rates faster than these, a different actuator should be chosen.

The key is to understand the deflection limits on the bandwidth specification. The analyst is well served by incorporating rate-limit elements in the mathematical models so that sensitivity to these will be checked, as it is the transition from the purely linear response to the on-the-rate-limit response which is particularly troublesome in terms of closed loop stability.

Given the sensitivity of many systems to rate-limit-induced Category 2 Pilot Induced Oscillations (PIO), it would be convenient if there were some effective guidance for selecting the relationship between bandwidth limits and open-valve rate limits in order to effectively eliminate rate-limiting trigger points. At present this seems to be done using tribal knowledge.

Gibson(2000) includes a striking example of this phenomenon, reproduced as Figure 4-7.

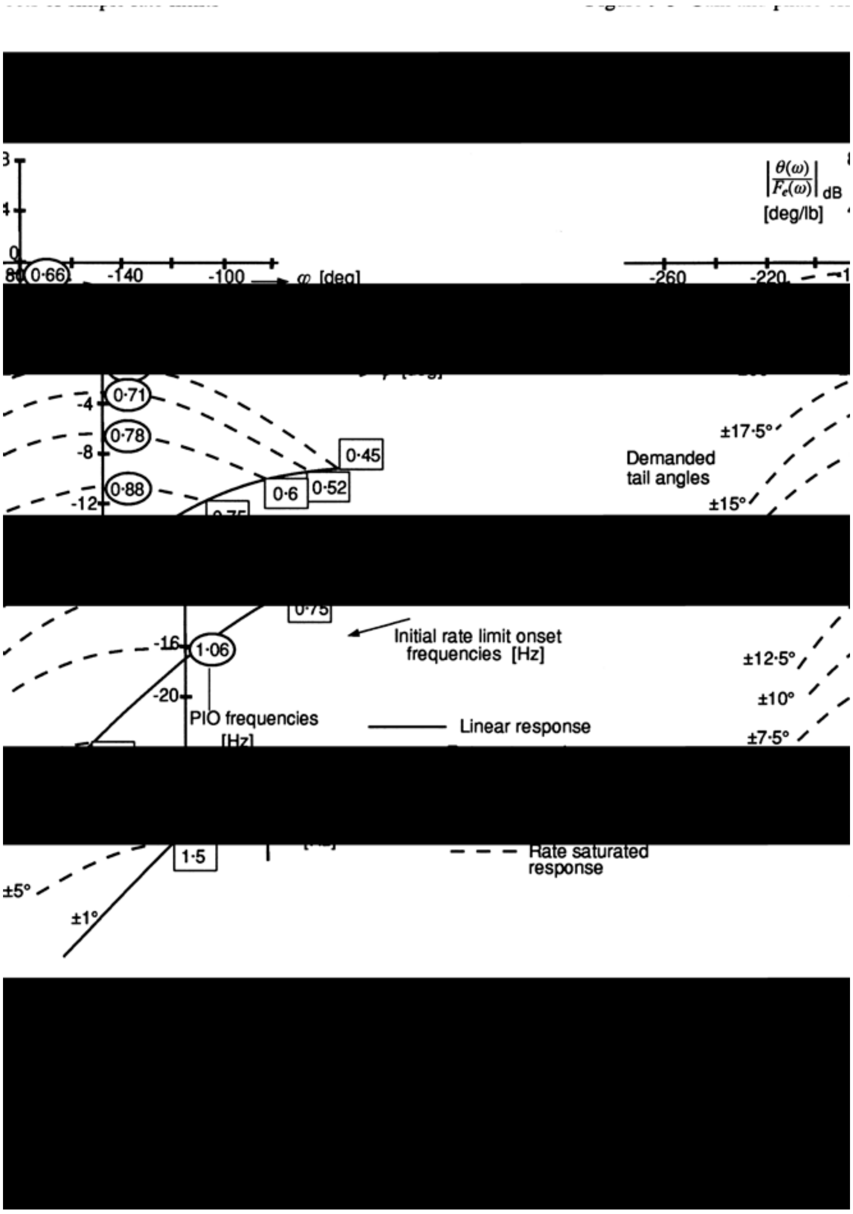

Figure 4-7 Effect of Actuator Rate and Acceleration Saturation on Phase/Gain Characteristics
(From Gibson (2000))

A second departure from linear characteristics similarly restricts the region of validity to near neutral deflection conditions: actuator performance under load. Of course, this is a strong function of flight condition. While the basic premise in deriving the equations of motion for the actuator is that piston motion is a function of the fluid flow rate, and flow rate is governed by the valve position, it is also true that the flow rate is a function of the pressure difference between the supply and the cylinder. When the cylinder is under load, particularly a near-limiting load, the difference in the pressure between the cylinder and the source might not be very great, and actuator performance will suffer.

Performance under aerodynamic load is important because, even though they may not be called out explicitly in the specifications, flight dynamics characteristics like damping, are required not only at all flight conditions, but at all deflections, i.e. not just at neutral, as well. Engineers should be aware that the no-load performance of an actuator can differ greatly from the loaded performance, and that can differ greatly across the deflection range, owing to airloads.

Figure 4-8 is a sketch after Raymond and Chenoweth (1993). This relates the no-load valve flow, on the vertical axis to the pressure across the ports on the horizontal axis as a function of valve position. Both of these parameters can be measured in the laboratory. Also depicted in Figure 4-8 is the region around neutral deflection, in which the actuator performance appears quite linear. Immediately it is apparent that results derived by assuming the linearity extends to the entire envelope could be seriously misleading.

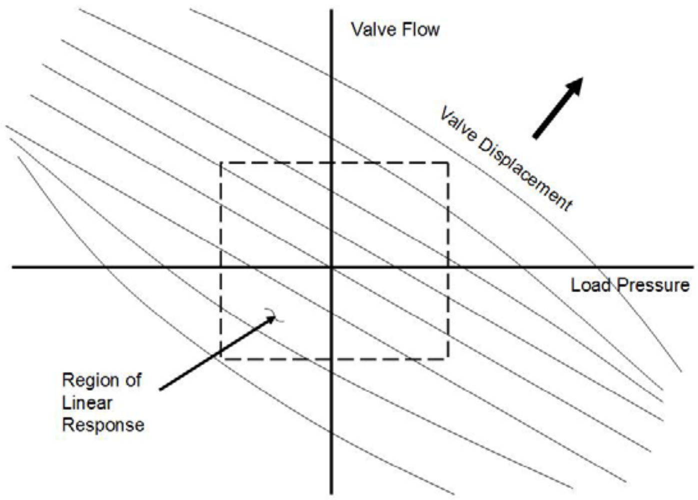

Figure 4-8. Typical Actuator Characteristics Under Load
(After Raymond and Chenoweth, 1993)

These considerations are important to the flight dynamics engineer for at least three reasons:

-Flight dynamics engineers need to understand the limits of analytical reliability of the models being used.

-There are frequently cases in which the flight dynamics engineer needs to model the full rate capability of the actuator (that is, dynamics which are limited by the limiting rate capability). In each instance, that the dynamic model is adequate for that purpose should be understood. If the model is not, a different model should be invoked.

-These nonlinear characteristics are very real, and in service, these limits will be violated on a regular basis. The consequences of these violations need to be understood. This implies that there is also a very real need for a nonlinear model which can function across the amplitude/frequency/flight condition spectrum. Frequently, linear models are used for design, and the design is then checked with nonlinear formulations. This is a very important step and should not be minimized.

Finally, the form of the actuator model is very important. Once it has been decided that for some limited analysis, a linear model of the actuator might be acceptable (notwithstanding the details previous), it must then be decided in what form this model should be built. Many authors have proceeded from first principles through various sets of assumptions (usually beginning with the fact that the actuator can be modelled with a linear differential equation) to arrive at various models for a hydraulic actuator with a mechanical input linkage. This was presented in Chapter 3.

The consequences of choosing a form of actuator model for analysis which does not substantially represent the real actuator lie in the resulting time delay difference. In the view of airplane handling qualities, time delay is very important. With this in mind, it is best to model all of the relevant parts which may contribute to time delay between the pilot's input and the airplane response in order to minimize the chance of being surprised in flight test.

It is illustrative to compare actuator forms by comparing their time domain amplitude responses to a step input. Figure 4-9 illustrates a first, second, and third order form, each at the same break frequency, and with the second and third order forms having the same damping. What is important to notice is that the second and third order forms contain what might be reminiscent of a time delay at the onset of the step, which here occurs at 1 second. The first order response does not exhibit this characteristic. Instead, it sees an instantaneous acceleration and begins moving immediately after the initiation of the step. At the point of maximum slope on the second and third order curves, a point at which some argue is where the pilot first begins to feel the response, the difference between the first order response and the second and third order responses in of the order of 40 – 50 ms. This is significant and indicates that the higher order actuator models are certainly justified for use in handling qualities analysis.

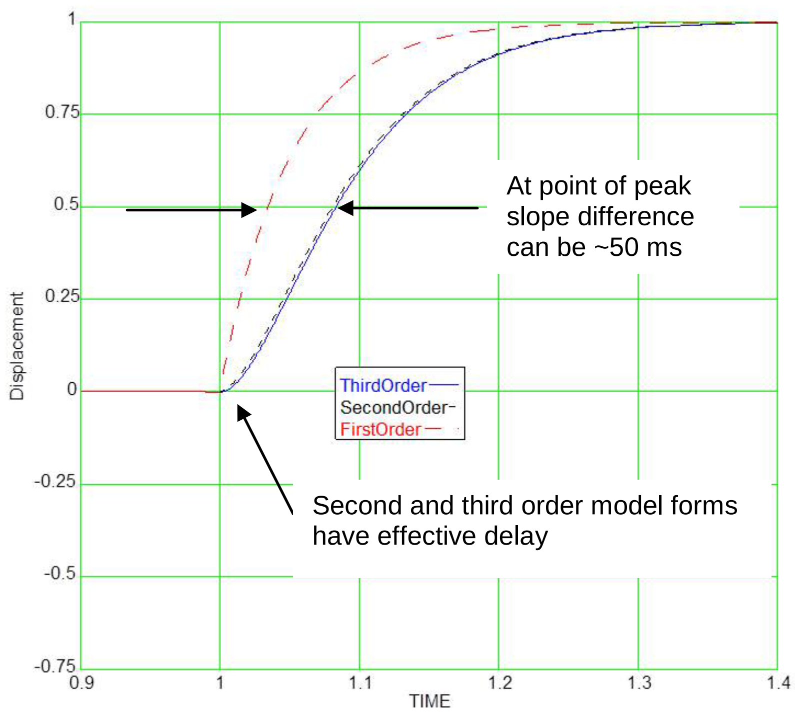

Figure 4-9. Actuator Performance Comparison.

This issue came to the author's attention during a test program using the US Air Force NC-131H Total In-Flight Simulation (TIFS) facility (Figure 4-10)* The issue at hand was what appeared to be a deficit in the model-following results: the airplane response was lagging the model. It was pointed out that if the model had a second-order actuator, then the TIFS results and those from the model would be much closer. This discussion was followed by a dedicated effort to measure in detail the performance of the rudder system on the TIFS airplane. The result of that effort was that the actual performance on the airplane was not quite as fast as advertised, and that the cause was structural compliance at the actuator attachment.

Figure 4-10. USAF Total In-Flight Simulation (TIFS) Facility.
(Photo courtesy of Calspan.)

* The mentioned experiment on TIFS was the last handling qualities experiment flown using that venerable airplane prior to its retirement. There was one other mission flown before going to Dayton, but it was a sensor mission, not involving piloted handling qualities. For more on where in-flight simulation fits in the handling qualities engineers' toolbox, see, e.g. Lee (2007).

This serves as a reminder to continually be on the lookout for violations of assumptions. The textbook derivation of actuation models discussed in Chapter 3 allow that the reduction from third-order to a simplified first-order form is done under the assumption of small applied loads. In the case of the TIFS experiment, the loads obviously were not “small”, and a higher-order actuator model was indeed appropriate. The difference, once again, between the performance of a first-order actuator model and a second- or third- order model looks for all the world like a time delay (ref. Figure 4-9). The central theme here is that *every* time delay needs to be properly accounted.

4.1.6 Summary of Modelling Issues

Large aircraft have been shown to exhibit slow modal frequencies. Moreover, the short period and phugoid modes tend to get closer together as airplane size increases. There is some evidence that pilots simply adapt by adopting new techniques, and this new technique is seen in time history analysis, it also suggests that pilots need an “internal model” to help them predict the effects of a given control input.

As stability is relaxed, short period natural frequencies get even slower, but perhaps more importantly, the character of the motion, as defined by the eigenvectors changes considerably.

With slow natural frequencies comes long times (in seconds) for any transients to die away. The consequence of this has been shown to be in the amplitude of the response. Essentially, pilots are seen as always being in the transient response, so whenever an input is made, it is made with a non-zero initial condition. This is not the case typically analyzed by designers.

All aerodynamic surfaces encounter unsteady lift development any time the flight condition, e.g. angle of attack changes. It has been shown that the length of time for this unsteady lift development to take place is a direct function of the size of the lifting surface chord. As airplanes get dimensionally larger, the lag associated with the unsteady lift may no longer be negligible for handling qualities analysis.

Because of size and speed ranges involved with large transport aircraft, control surfaces are moved by hydraulic actuators. These are typically modelled in simulation, but the form of the model is important. Simple first-order models typically used are not conservative in terms of the phase contribution they bring to the whole motion of the airplane, and the contribution can be significant.

4.2 Pilot Manipulator Feel Characteristics

4.2.1 Threshold Measurements

In order to precisely control the airplane, pilots need to be able to precisely control the manipulator itself. A number of single-degree-of-freedom experiments were conducted in an attempt to understand how pilots view the balance between force, force gradient, and nonlinear elements in their ability to position the control inceptor, In these, the pilot was not asked to perform a piloting task, but rather, simply to position the control (in the case to be discussed, the control wheel, but other axes were studied). The pilots were asked to move the control wheel in a stepwise fashion. That is, they were instructed to move the wheel in a series of steps: step and hold, step and hold, but each time, they were to make the size of the step as small as physically possible. Pilots were not given any time constraints, or any other auxiliary tasks to perform.

Simulation

The experiments were conducted in a transport category simulation cockpit with electric control loading. Wheel dimensions corresponded to that of typical commercial transport aircraft. Wheel deflection was noted with an index on top of the control column, so the pilot had immediate access to wheel deflection. Forces and positions were measured via the control loader instrumentation system.

Participants

Five pilots participated in the experiments including 3 experimental test pilots, one F-16 pilot, and one commercial pilot.

Flight Condition

This series of experiments was conducted with the simulation set on the ground, not moving. The control loading scenario is that of a fixed spring, and it was a single-degree-of-freedom wheel positioning experiment, so flight condition did not matter.

Configurations

The configurations consisted of 3 variations of breakout, 3 variations of friction, and 3 variations of spring gradient. The parameter values matched those used for the handling qualities experiments reported later.

Task

The pilot was asked to move the wheel from neutral to one stop, then reverse through neutral to the other stop, moving the wheel in steps, and minimizing the step size. The pilot was told that the point of the experiment was to determine the minimum step size possible.

The point of having them go all the way to full wheel was to see if the total force changed the size of the step they were able to produce. The point of returning was to see if they were able to relax with the same degree of precision that they had in adding force.

The task was repeated using the pilot's dominant hand, the non-dominant hand, and using both hands.

Figure 4-11 shows one pilot performing this task. This was a case of Two-Hands moving to the Right. A sample of the data is presented in Figure 4-12.

Analysis

Observation of the task conduct and examination of the data indicates that what the pilot was actually doing imparting an impulse to the wheel by gripping with thumb and fingers and allowing the heel of his hand to impart the impulse.   The challenge was to find the smallest possible step size. Obviously the pilot did not have the resolution to see that the "steps" were actually "sawteeth", and once he got the wheel to move, he damped it with his grip and let the friction hold it in the new location. For this condition the total force was well within one-hand limits, so it only got fatiguing after a while. In the two-handed cases, the pilots would use their other hand as a damper, while imparting an impulse to the wheel.

Figure 4-11. Wheel Step Tracking
(Photo courtesy of Boeing)

Close examination of the data indicates that the impulses are nearly symmetrical in force and position, suggesting a completely open-loop control strategy. This is not what was being asked, but it does provide interesting insight on what they prefer to do if left to their own devices. The data detail is shown in Figure 4-13.

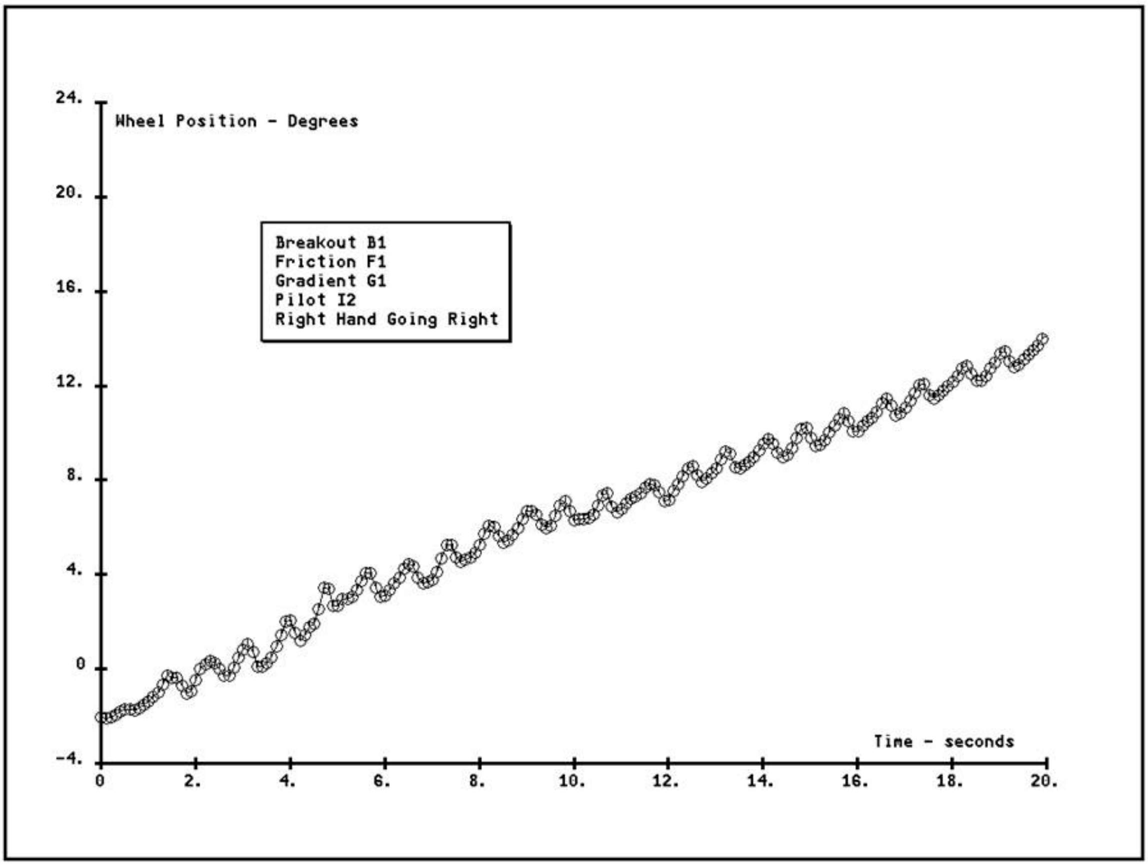

Figure 4-12 Stepwise Wheel Inputs

A sample of the analysis results is given in Figure 4-14. From the data in the figure, it's clear that two hands are more consistent than one hand; and that the steps were larger on each end than in the middle. Just how much of that was due to the breakout force and associated gradient change on the low end and the higher total forces on the high end is not known. It is also possible that there is an effect of geometry. Right hand going Left (over the top of the wheel) is always easier than Left hand going Left (under the bottom of the wheel, particularly for a right-handed pilot. In addition, the two handed case was flown with larger breakout force, which also means that there is larger total force for the whole deflection range.

This data is useful because it informs about human performance thresholds: what the pilot is just able to achieve given no distractions, no other tasks, and a concentrated effort. The reason this data was sought is because there is evidence to suggest that "operational" thresholds are several times greater than absolute human performance thresholds.

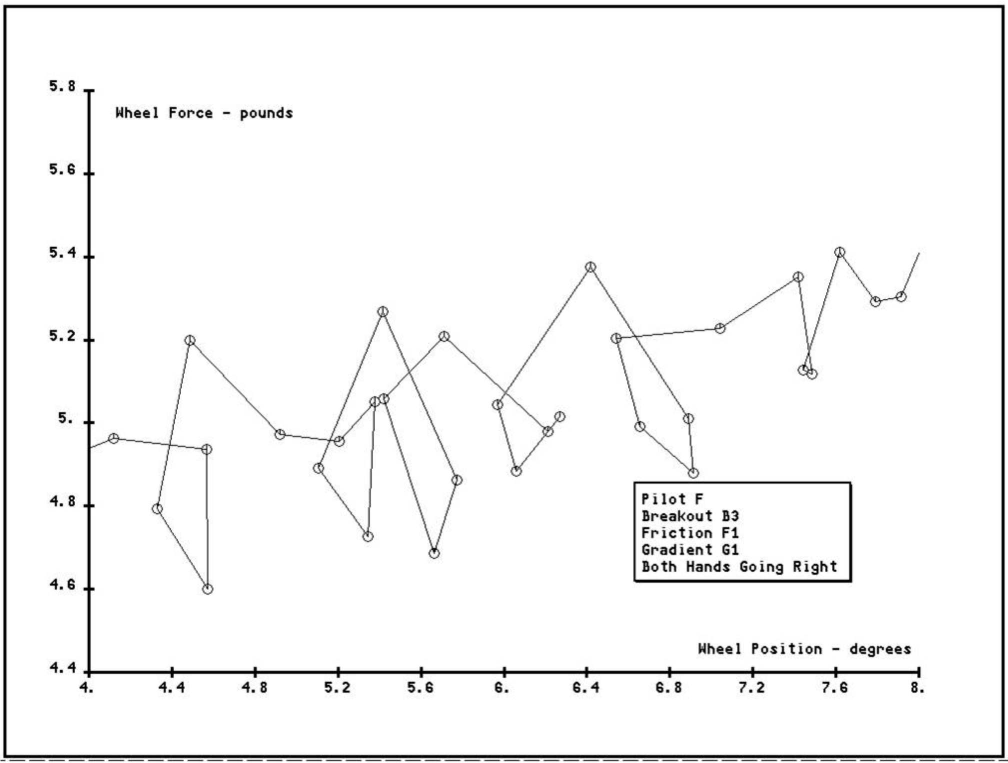

Figure 4-13. Details of the Stepwise Wheel Data

That is to say that if a pilot can just achieve 0.4 degrees of wheel motion when he's really trying to minimize it, then the minimum we should expect from him when he's in the course of doing other things, is larger than that. Silvestrov, Koziorov, and Ponomarenko (1986) suggest that operational thresholds are 10-15 times the differential thresholds. Kotic, (1971) suggests that operational thresholds are 10 times the differential thresholds. If that's true, and this data applies, it would suggest that 4 pounds of breakout force might be appropriate.

Data were also collected for pedals, but is not reported here.

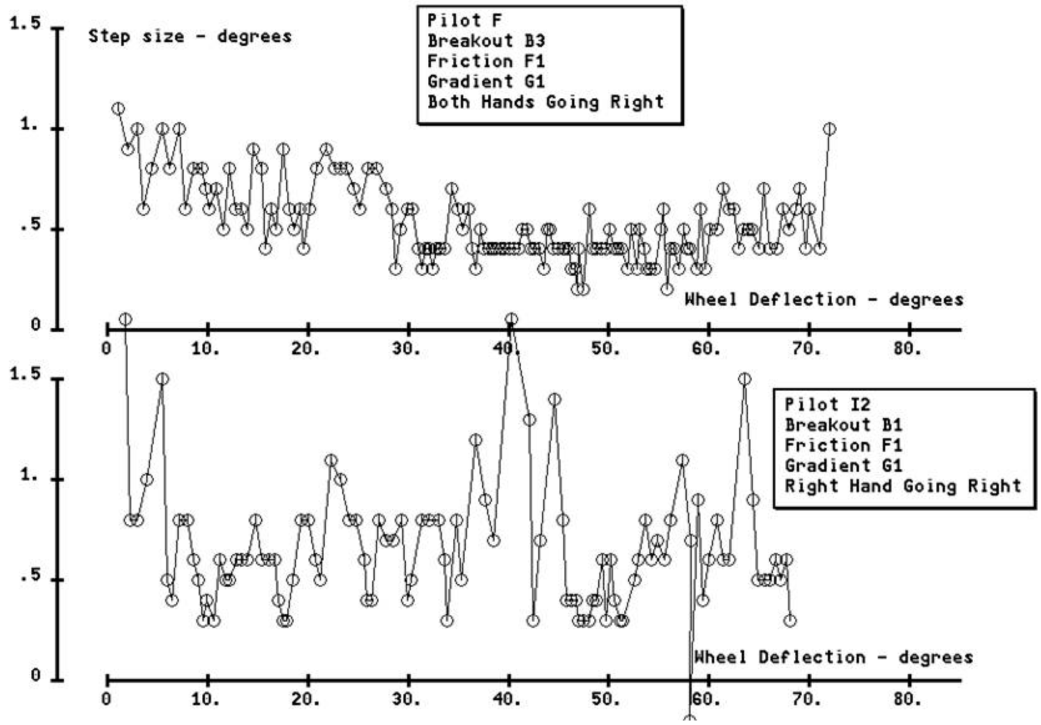

Figure 4-14. Stepwise Wheel Inputs Analysis

4.2.2 Optimizing the Feel Characteristics for Good Handling

Rodchenko, et al* introduced to the West a method to generate optimized feel system gradients for given manoeuvres based on their earlier work in Russia. Methods were developed based on those of Rodchenko, et al to extend this work to large displacement wheel-column controllers in the lateral axis. This extended work was first published in Lee, Rodchenko, and Zaichik (2003). The methods were then validated, refined, and generalized. This refinement required additional experiments, summarized below. Further, a simplified graph-analytical method was developed for selection of feel system characteristics (friction and breakout for a given gradient and natural frequency.) Thereafter, they were applied again to pedal feel characteristics (Lee, Rodchenko, Zaichik, and Yashin, 2005) to complete the lateral-directional

* See for example Rodchenko, Zaichik, Yashin, Perebatov, and Lyasnikov, (1994a), Rodchenko, Zaichik, Yashin, Perebatov, and Lyasnikov, (1994b), Rodchenko, Zaichik, and Yashin, (1996), Rodchenko, Zaichik, and Yashin, (1998), Rodchenko, Zaichik, Yashin, Lyasnikov, Galyuchinko, and Rofov, (1995)

axis definitions for feel and sensitivity. What is described here follows the summary in Lee, Rodchenko, and Zaichik (2004) of the method.

Experiments

Simulation experiments were conducted in a number of stages both to explore the effects likely to be encountered in practice and to collect specific validation data to demonstrate the theoretical methods developed. The first set of experiments were documented in Lee, Rodchenko, and Zaichik (2003). The second set documented in Lee, Rodchenko, Zaichik, (2004). The second set of data included expanded ranges of friction and breakout forces, and considered the effects of damping, wheel inertia, and control sensitivity.

Simulations

Experiments were flown in both the TsAGI FS-102 motion-base simulator at Zhukovsky (Figure 4-15), and the Boeing M-Cab motion base facility in Seattle (Figure 4-16). Both simulator facilities were configured as wide-body transport cockpits, with high quality visual, motion and control loading cueing.

Figure 4-15. TsAGI's FS-102 Transport Simulator Facility (Lee, Rodchenko, and Zaichik, 2004)

Figure 4-16 Boeing Multi-Purpose Engineering Simulator
Photo courtesy of Boeing.

Participants

Both sets of experiments included three test pilots from the Gromov Flight Research Institute of Russia* and two from Boeing. All participant pilots were experimental test pilots well versed in conducting handling qualities evaluations. Because of scheduling constraints, not all pilots flew all configurations.

Flight Conditions

All conditions were flown at landing flaps at a normal reference speed for the airplane configurations tested. All configurations were at mid CG, maximum landing weight. Wind conditions included calm, crosswinds to 25 knots, turbulence intensity to moderate.

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* It should be noted when evaluating the data from these tests that Russian pilots tend to provide Cooper-Harper ratings to a resolution of 0.1. This has been discussed many, many times with them. Their position is that Cooper-Harper is a tool to aid in the communication between pilot and engineer. If they want to communicate that a configuration is not as bad as a 3 but better than 2, they want to be able to do that. In conducting these experiments, several blind repeat conditions were included to ensure that the high-resolution ratings were consistent. They were.

Configurations

In addition to three values of spring gradient, 8 values of breakout force, 7 values of friction, three inertias, were tested. Not all pilots flew every configuration, and not all permutations were flown.

Tasks

Pilots were asked to fly normal and crosswind landings. They were also asked to fly a so-called “gust” landing, in which a large (25 knot) crosswind was initiated at a specific (not known to the pilot) altitude on the approach, precision offset landings, and what the pilots referred to as “free piloting”, in which they experimented on their own to gain an impression of the configuration.

Data

The raw data were plotted on a map of friction vs. breakout force for each gradient, damping ratio, inertia, and control sensitivity gain. A template of this map is shown in Figure 4-17. In order to orient the reader, Figure 4-17 also depicts notional hysteresis curves to illustrate the shapes of the characteristics in different regions of the map.

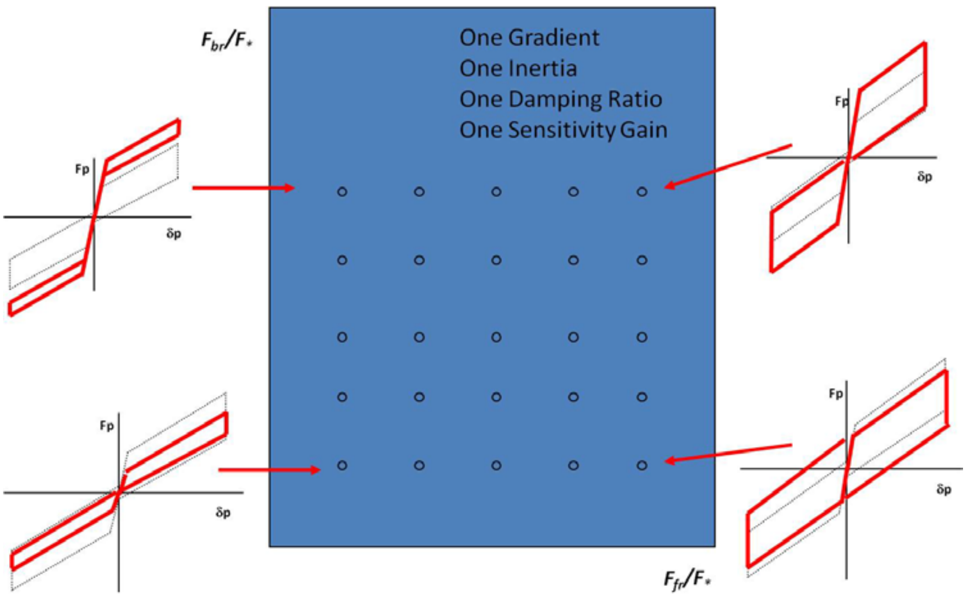

Figure 4-17 Mapping of Feel System Data

In Figure 4-17 and 4-18, the axes are normalized by an arbitrary friction force F*. In each of the notional sketches showing displacement-force hysteresis curves, the gray curves are to illustrate a “nominal” hysteresis. For example, in the lower right, characterized by large friction, very small breakout, the very fat red hysteresis loops illustrate that such a configuration would exhibit poor centring. Diagonally across the map, the very small friction combined with very large breakout would demonstrate very “snappy” centring.

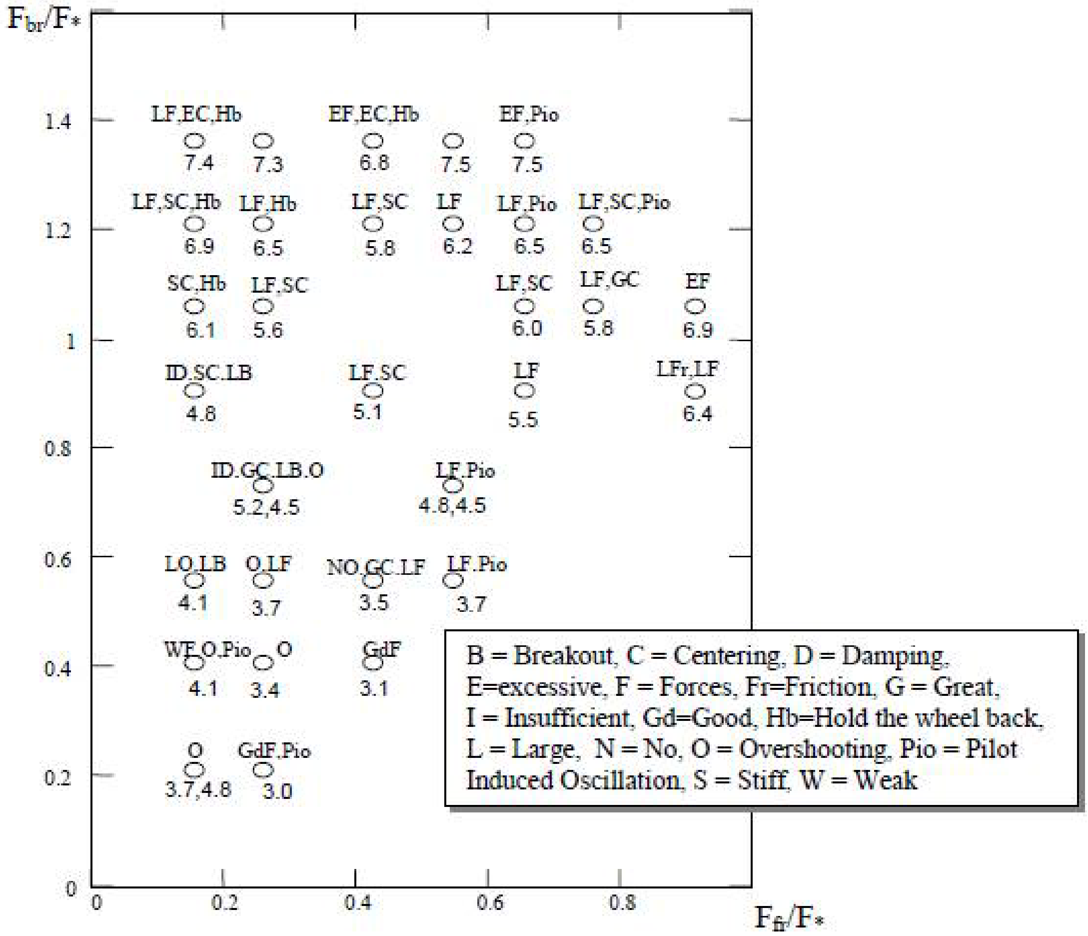

Figure 4-18. Summary of Data Collected During Feel System Evaluation

Detailed pilot comments via formal comment cards, measured touchdown parameters and pilot opinions via Cooper-Harper ratings were recorded. An example summary from the second set of data (much larger values of friction and breakout, to identify the Level 2/3 boundry) are included in Figure 4-18. In this summary plot (for one gradient, one damping, etc.), pilot comments are summarized via a “shorthand”. The comments are listed in the box in the figure. The average handling qualities ratings are shown beneath each data point on the map. This provides not only the ratings, but the pilot’s reason for assigning the ratings.

Describing the Theoretical Method Developed

Underpinning the method to select optimum feel system characteristics are a number of assumptions:

- The effect of feel system characteristics on handling qualities depends only on:
    - Applied forces ($\overline{F}$)
    - Controller displacements ($\overline{\delta}$)
    - Feel system overshoot (Δ)
    - Feel system response time (t_r)
- There is an optimum combination of these parameters, ($F_*, \delta_*, \Delta_*, t_{r*}$) which does not depend on feel system characteristics, control system sensitivity, or airplane dynamic performance.
- When the parameters $\overline{F}$, $\overline{\delta}$, Δ, t_r deviate from their optimum values, the handling qualities should be expected to deteriorate.
- If the values of some of the parameters involved in the force/displacement of the controller are given, the others should be chosen so that $\overline{F}$, $\overline{\delta}$, Δ, and t_r are close to their desired values.
- The aircraft state parameters (ϕ, p, …) may be assumed to be independent of the manipulator and control sensitivity characteristics and aircraft dynamics. This assumption is that the pilot will try to get the airplane to perform the same manoeuvre regardless of the manipulator or sensitivity characteristics. The pilot will try to use the same roll rates, achieve the same turn radius, etc. Regardless of the feel system and other parameters. The pilot may need larger displacements or smaller

forces, and might not like the resulting forces or displacements, but in general, he will do what is necessary to perform the manoeuvre.

There are two general problems to be solved: first, to find the optimum combination; second to find the boundaries of permissible characteristics for different levels of Handling Qualities.

The optimum will be found to satisfy the condition:

$$\min_{F_\delta, F_{bf}, F_{fr}, \ldots} J(\overline{F} - F_*, \overline{\delta} - \delta_*, \Delta - \Delta_*, t_r - t_{r*}) \tag{4.5}$$

The permissible values for a given level of handling qualities will satisfy the condition:

$$\overline{F} = F_{per}\,,\ \overline{\delta} = \delta_{per}\,,\ \Delta = \Delta_{per}\,,\ t_r = t_{r\,per} \tag{4.6}$$

In which J is the monotonic cost function with its minimum at

$$\overline{F} = F_* = const\,;\ \overline{\delta} = \delta_* = const\,;\ \Delta = \Delta_*\,;\ t_r = t_{r*} \tag{4.7}$$

F_δ, F_{bf}, F_{fr} ,…are feel system characteristics (e.g. spring constant, breakout force, friction force, etc.);

$\overline{F}$, $\overline{\delta}$, Δ, t_r are the values of the generalized parameters, which themselves are functions of the feel system characteristics:

$$\begin{aligned} &\overline{F} = \overline{F}(F_\delta, F_{br}, F_{fr}, \ldots); \overline{\delta} = \overline{\delta}(F_\delta, F_{br}, F_{fr}, \ldots) \\ &\Delta = \Delta(F_\delta, F_{br}, F_{fr}, \ldots); t_r = t_r(F_\delta, F_{br}, F_{fr}, \ldots) \end{aligned} \tag{4.8}$$

The cost function J can be assumed to be the pilot rating increments

$$J = \Delta HQR((\overline{F} - F_*), (\overline{\delta} - \delta_*), (\Delta - \Delta_*), (t_r - t_{r*})) \tag{4.9}$$

caused by the deviation of $\overline{F}$, $\overline{\delta}$, Δ, and t_r from their optimum values. Close to optimum, this function ΔHQR may be approximated by:

$$\Delta HQR = k_F(\overline{F} - F_*)^2 + k_\delta(\overline{\delta} - \delta_*)^2 + k_\Delta(\Delta - \Delta_*)^2 + k_{t_r}(t_r - t_{r*})^2 \qquad (4.10)$$

This would be sufficient if the functions in equation (4.8) could be identified. To do this, the notion of "characteristic forces and displacements" must be defined. Study of time histories, recording of pilot comments, and conversations around the evaluation process used by pilots reveals that when pilots comment about "forces" exerted to perform some manoeuvre, what they are really talking about is the force required to go outbound from a neutral control position, i.e. region I in Figure 4-19. This is corroborated by experience with systems which have positive centring (and all Part 25 certified systems will) in that moving outbound from neutral requires overcoming the breakout, friction, and spring gradient, but returning to neural may not require any force at all.

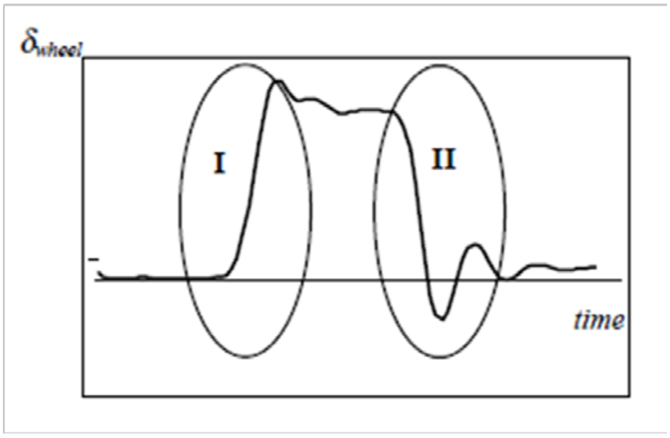

Figure 4-19 A pulse-type input, typical of pilot making a small correction to roll attitude.

Further, in accordance with the last assumption above, the pilot will try to achieve a certain "characteristic" performance, so it is assumed that in performing normal flying tasks, the pilot will manipulate the controls as necessary to try to achieve, say, a roll rate p=p*, where p* is the "characteristic" roll rate.

It should be mentioned at this point, that the analysis will not take into account (for the time being) the effects of control system inertia or control system damping, and that it is assumed there is a direct link between controller displacement and surface displacement.

Then, if δ_p is the roll control sensitivity, given as wheel deflection per unit of steady state roll rate,

$$\bar{\delta} = \delta_p p_* \qquad (4.11)$$
$$\bar{F} = F_{br} + F_{fr} + F_\delta \bar{\delta}$$

Similar to the discussion with pilots regarding their assessment of applied forces, when the pilots comment about feel system *dynamic performance*, it becomes clear that their decisions are based primarily on the motion of the wheel towards neutral: they dislike either having to pull the wheel back to neutral if it is too sluggish, or having to "hold it back" if it is too quick. Some of these comments are tempered as well by knowledge of typical structural dynamic response of large airplanes: moving the wheel too quickly can in some cases generate undesirable structural dynamic motions which annoy pilots and passengers alike. So pilots like wheel controllers which move at a velocity which is "just right".

The feel system dynamics were assessed in terms of natural motion of the "relaxed limb-wheel", since pilots typically do not simply let go of the controller when returning it to neutral. The fact that their hand rides along makes it necessary to understand the effect of the limb on the controller dynamics. The motion of the manipulator (wheel) is given by:

$$(m + m_{pilot})\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_\delta \delta + F_{fr}\ \mathrm{sgn}(\dot{\delta}) + F_{br}\ \mathrm{sgn}(\delta) = 0 \qquad (4.12)$$

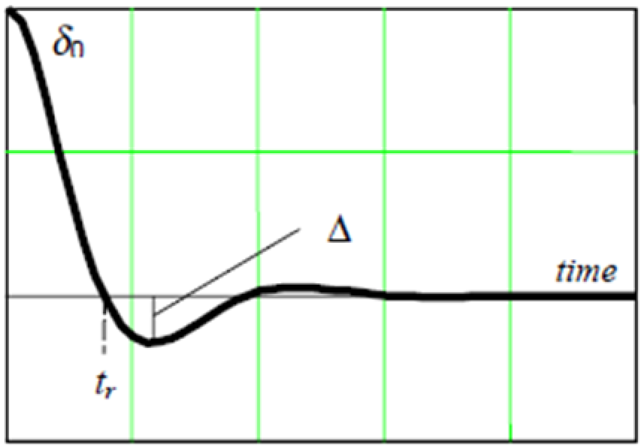

Figure 4-20 Response Time and Overshoot Defined

Representative pilot limb mass was measured and reported in Lee, Rodchenko, and Zaichik, (2003) and was found to be a sizeable percentage of the otherwise mechanical system mass.

The notions of "overshooting" and "response time" are illustrated in Figure 4-20.

If a system can be described by a second order differential equation, (e.g. Equation (4.12) if F_{fr} and F_{br} are zero), it is possible to arrive at closed-form solutions for overshooting and response time. For the nonlinear system of Equation (4.12), it is not possible to find expressions for parameters Δ and t_r. The analysis can be simplified if Equation (4.12) is expressed in dimensionless form. This is facilitated by the introduction of dimensionless time and dimensionless wheel displacement:

$$\tau = \sqrt{\frac{F_{\delta}}{m + m_{pilot}}} \bullet t\,; \; \tilde{\delta} = \frac{\delta}{\delta_0} \tag{4.13}$$

Substituting these into Equation 4.12 produces

$$\ddot{\tilde{\delta}} + 2\varsigma\dot{\tilde{\delta}} + \tilde{\delta} + \tilde{F}_{br}\,\mathrm{sgn}\,\tilde{\delta} + \tilde{F}_{fr}\,\mathrm{sgn}\,\dot{\tilde{\delta}} = 0 \tag{4.14}$$

Where

$$\zeta = \frac{F_{\dot{\delta}}}{2\sqrt{F_{\delta}(m + m_{pilot})}}\,; \; \tilde{F}_{br} = \frac{F_{br}}{F_{\delta}\delta_0}\,; \; \tilde{F}_{fr} = \frac{F_{fr}}{F_{\delta}\delta_0} \tag{4.15}$$

Using the dimensionless equations in this way reduces 7 parameters in Equation (4.12) to 3 parameters, which greatly simplifies the analysis.

Peculiarities regarding Level 2 dynamic performance.

The pilot comments gathered during experimental trials indicate that when the breakout and friction forces get large, the pilots have to consciously "hold back" the wheel when returning to neutral (at least as long as breakout is larger than friction). This violates the assumption on which Equation (4.12) is based, that the "relaxed limb-manipulator" rides the wheel back to neutral with zero force application. For Level 2 handling qualities, the pilot ratings are determined not by t_r, but by the level of forces exerted as the wheel is returning to neutral, i.e. $F^- = F_{br} - F_{fr} + \delta F_\delta$. Therefore, for Level 2, the pilot ratings are accounted for not by the feel system which returns to neutral too quickly as in Figure 4-20, but they are determined by the wheel forces $\overline{F}^-$ for wheel displacements of $\overline{\delta} = \delta_p p_*$

$$\overline{F}^- = F_{br} - F_{fr} + \delta_p p_* F_\delta . \tag{4.16}$$

Desirable and Permissible Values

The desirable and permissible values of the static and dynamic characteristics $\overline{F}$, $\overline{\delta}$, Δ, t_r, $\overline{F}^-$ and the values of the weighting coefficients k_F, k_δ, k_Δ, and k_{t_r} in Equation (4.10) depends on the type of manipulator and the control axis. There are different ways to determine them.

The values for desirable and permissible levels of parameters Δ and t_r and the weighting coefficients $k\Delta$ and k_{t_r} can be determined from experimentally determined ratings $\Delta HQR(\varsigma)$, and $\Delta HQR(m)$ for a linear feel system without friction or breakout. For a linear system, there is a one-to-one correspondence between damping and inertia and overshoot and response time. This allows determination of $\Delta HQR(\Delta)$ and $\Delta HQR(t_r)$ as indicated in Figure 4-21. This then allows selection of values for desirable and permissible levels of Δ and t_r and values of k_Δ and k_{t_r}.

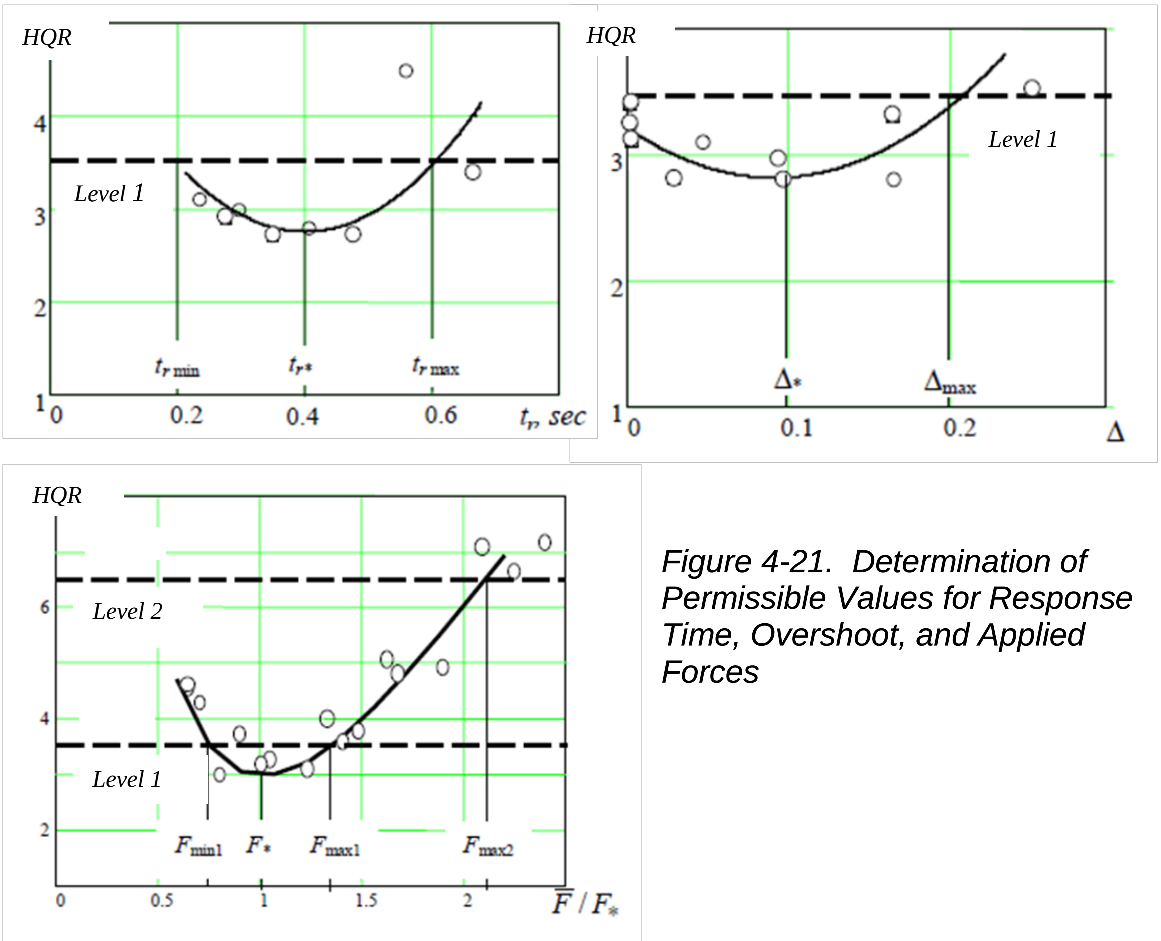

Figure 4-21. Determination of Permissible Values for Response Time, Overshoot, and Applied Forces

The values of characteristic force $\overline{F}$ and the weighting coefficient k_F can be determined from the experimental data for nonlinear feel systems. This is illustrated in Figure 4-21, which shows pilot ratings as a function of $\Delta PR(\overline{F})$. This function was constructed using Equation (4.11) and the data from Figure 4-18 along a line for $F_{br} \approx F_{fr}$. This is valid because if $F_{fr} = F_{br}$, the variation of $F_{fr} + F_{br}$ causes only a variation in force while the values Δ and t_r remain nearly constant. If there are any pilot rating changes along this line, they must be caused by only a variation in $\overline{F}$.

Based on review of data for the manoeuvres flown and detailed conversations with pilots during those experiments, the parameter $\overline{\delta}$, the characteristic deflection desired for normal flying is estimated to be 30% of full travel for any manipulator, i.e. $0.3\delta_{max}$. The weighting coefficient k_δ is estimated to be

$k_\delta = 18 \cdot k_f$ based on the experience of Zaichik, et al (1990) and Rodchenko, Zaichik, and Yashin (1998).

Graph-Analytical Method

Since it is not possible to exactly define the optimum values of the characteristics (*F_{br}, F_{fr}, F_δ,* …) for the case of a system defined by nonlinear differential equations, it is desirable to find another, simpler method to achieve the same result. In this example, it is applied to the optimization of friction and breakout, but it can be applied in a similar way to any of the other parameters of the feel system. The method consists of constructing lines of constant parameter values for $\overline{F}(F_{br}, F_{fr}, F_\delta, ...) = const.$, $t_r(F_{fr}, F_{fr}, F_\delta, ...) = const.$, $\Delta(F_{br}, F_{fr}, F_\delta, ...) = const.$ (and $\overline{F}^{-}(F_{br}, F_{fr}, F_\delta, ...) = const.$ instead of t_r=*const*. and Δ=*const*. for Level 2 boundaries) in the plane of *F_{br}, F_{fr}*. Each of these are straight lines in the friction vs. breakout plane. The point at which the curves of:

$$\overline{F}(F_{br}, F_{fr}, F_\delta, ...) = F_*; \quad (4.17)$$

$$t_r(F_{br}, F_{fr}, F_\delta, ...) = t_{r*} \text{ ; and} \quad (4.18)$$

$$\Delta(F_{br}, F_{fr}, F_\delta, ...) = \Delta_* \quad (4.19)$$

all cross, defines the minimum of the function given by equation 4.3. This point defines the optimum combination of F_{br} and F_{fr}.

If the curves do not cross at the same point, it is assumed that the optimum point is found within the area made up by the crossing lines (see Figure 4-22). Referring to Figure 4-24, it is seen that the pilot ratings do not change in this region, so it is assumed that the optimum combination is equally spaced from these curves, i.e. in the centre of a circle inscribed into the triangle made up by the lines $\overline{F} = F_*$, $t_r = t_{r*}$, and $\Delta = \Delta_*$ (Figure 4-22).

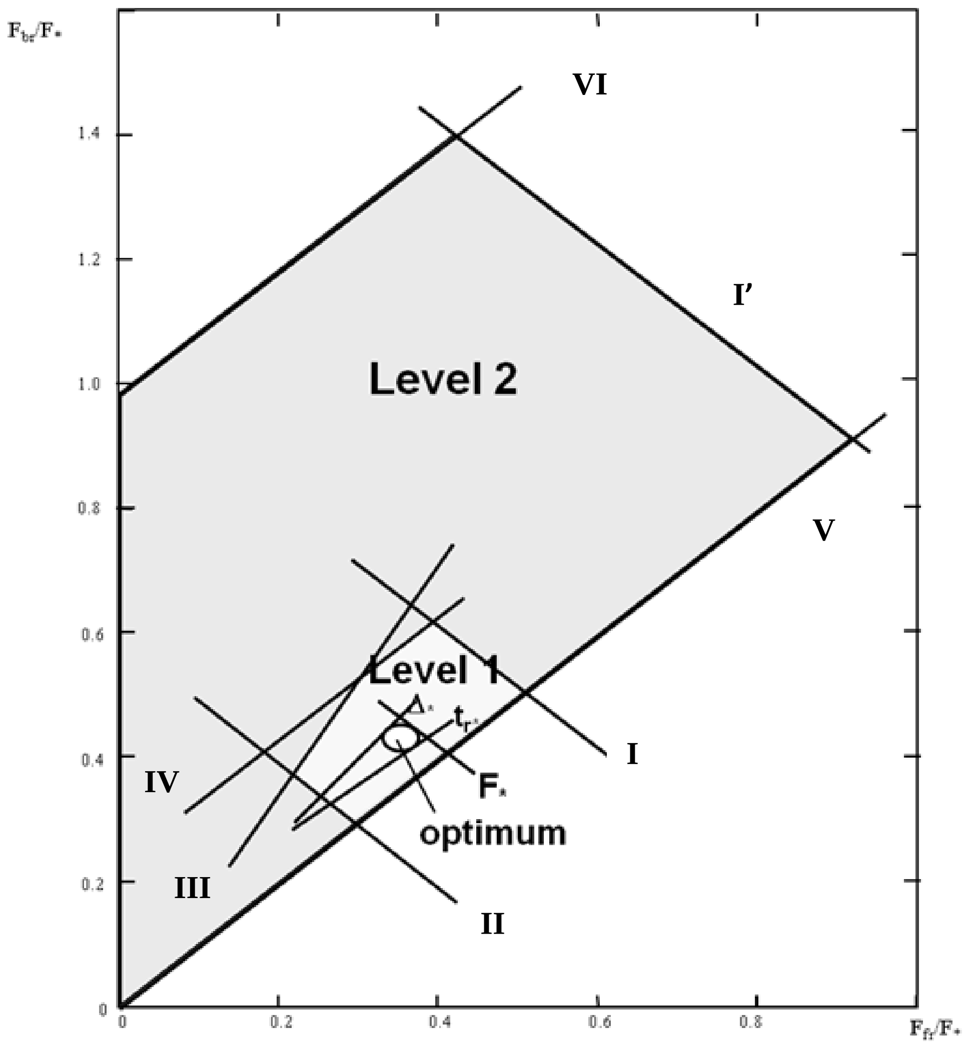

Figure 4-22. Construct of graph-analytical method.

To construct the whole map including the Level 1 / 2 boundaries, it is necessary to find lines of :

- Minimum and maximum permissible $\overline{F}$ (seen as lines I and II in Figure 4-22)
- Maximum permissible values of Δ (line III in Figure 4-22); and
- Minimum permissible value of tr (line IV in Figure 4-22).

In order to ensure positive centring, it is easy to see the need for a line corresponding to $F_{br}=F_{fr}$, since if friction is larger than the breakout force, the wheel will not centre.

In addition, it should be noted that the minimum value of overshoot *(Δ=0)* corresponds to pilot ratings within Level 1 in Figure 4-21, it is not necessary to construct a line bounding minimum Δ. Also, for feel characteristics typically used, the maximum response time is very close to the line for positive centring, and in fact, usually below it, so there is no need to construct a line for maximum response time t_r. Figure 4-21 showed the Level 1 / 2 boundary values of t_r and Δ for a wheel controller are $t_{r_{\min}} = 0.2\,\text{sec.}$, and $\Delta_{\max}$=0.2 (20%).

The measured data in Figure 4-21 suggests that when control forces $\overline{F}$ become about 1.3 times greater or less than optimum (F_*), the pilot ratings deteriorate. Therefore, it is assumed that permissible (Level 1 boundary) values of applied forces are $F_{\min_{1/2}} = 0.7F_*$ and $F_{\max_{1/2}} = 1.3F_*$.

Determining the maximum permissible boundary for Level 2 forces $\overline{F}$ (line I' in Figure 4-22) can be done in a way similar to that for the Level 1 boundary. Minimum permissible forces, along with maximum permissible overshoot is bounded by the centring constraint, so these are not issues. As noted above, the boundary for permissible t_r is replaced by a boundary representing objectionable forces required to hold the wheel back while returning to neutral: $\overline{F} = \overline{F}^-$ (line VI in Figure 4-22).

According to measured data and pilot comments, $F_{\max 2/3} = 2.2F_*$; $\overline{F}^- = 1.3F_*$.

Determination of the boundary curves (equal $\overline{F}$, Δ, t_r, $\overline{F}^-$)

Lines of constant $\overline{F}$ can be derived from:

$$F_{br} + F_{fr} + F_{\delta}\delta_p p_* = \overline{F} = const. \tag{4.20}$$

Equations for lines of optimum and permissible pilot forces can be found by substituting F_*, $F_{\min 1/2}$, $F_{\max 1/2}$, or $F_{\max 2/3}$ for $\overline{F}$. From this expression it is clear that lines of constant $\overline{F}$ are straight lines inclined at -45 degrees.

Lines of constant Δ are not so clear. Equation 4.12, though, illustrates that overshoot depends on ς, $\tilde{F}_{br}$, and $\tilde{F}_{fr}$. The curves of constant Δ in the plane of dimensional F_{br} and F_{fr} can be drawn with the help of Figure 4-23, in which the curves are in terms of dimensionless $\tilde{F}_{br}$ and $\tilde{F}_{fr}$.

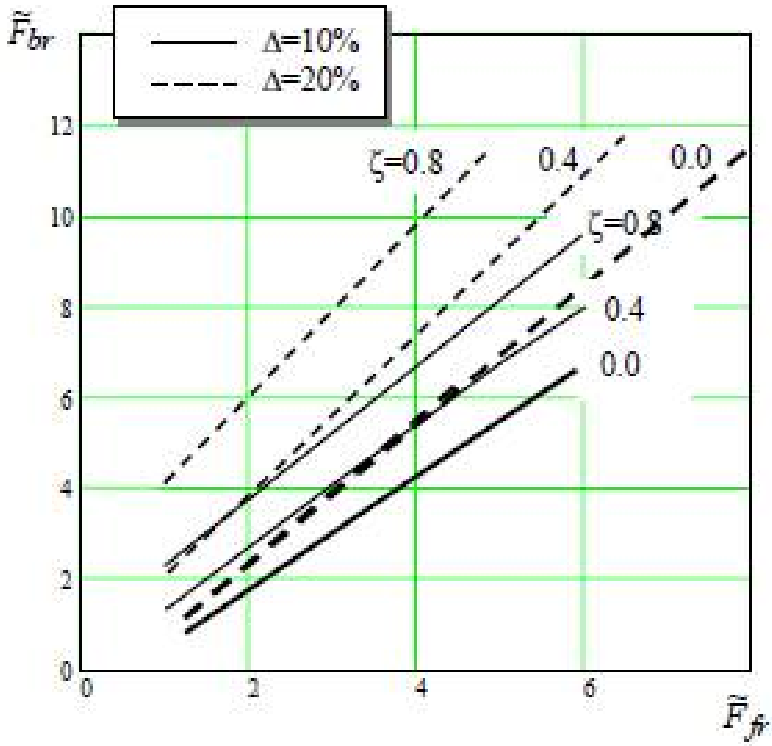

Figure 4-23. Curves of equal Δ in terms of dimensionless friction and breakout.

To generate curves of constant t_r, equation 4.14 can be re-arranged as:

$$\tilde{F}_{br} - \tilde{F}_{fr} = \frac{e^{-\varsigma\tau_r}\sin(\sqrt{1-\varsigma^2}\tau_r + \varphi)}{\sqrt{1-\varsigma^2} - e^{\varsigma\tau_r}\sin(\sqrt{1-\varsigma^2}\tau_r + \varphi)} \qquad (4.21)$$

Now assume the right hand side to be of the form K(ς, τ_r) to get the dimensional form:

$$F_{br} - F_{fr} = \delta_0 F_\delta K(\varsigma, \omega, \tau_r). \qquad (4.22)$$

This describes straight lines inclined at 45 degrees. That is, they are parallel to the line of F_{br}=F_{fr}, shifted by $\delta_0 F_\delta K(\varsigma,\omega,t_r)$.

Lines of constant $\overline{F}^-$ can be found from Equation 4.14:

$$F_{br} - F_{fr} + F_\delta \delta_p p_* = F_{per}^- \qquad (4.23)$$

It is clear that this describes straight lines at 45 degrees.

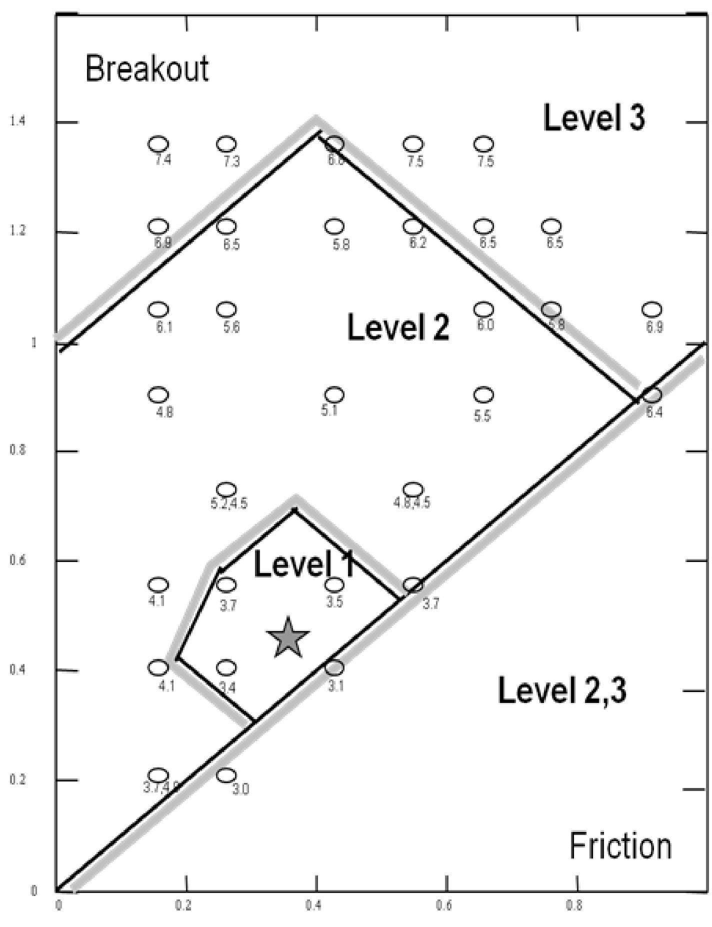

Figure 4-24. Comparison of graph-analytical method to measured results.

The validity of the graph-analytical results can be seen by comparing the derived boundaries with the raw pilot rating data, Figure 4-24. That is, when the boundaries, defined by the straight-line equations are plotted on the raw data from the experiments, there is a good correlation with HQR=3.5 and HQR=6.5. In addition, the location of the analytically defined "optimum", identified by the star symbol, is verified by comparing to the HQR's measured.

4.2.3 Extension of Hess Linearity Criterion

Hess' Linearity Index was introduced and discussed in Chapter 3. There, it was noted that the index as presented (Hess, 2004) was really only applicable to the case in which friction and breakout forces were equal. Here, that construct is extended to include cases in which breakout and friction are not equal.

Extensions and Modified Linearity Indices

While Hess' approach has considerable merit, the constraint that Breakout and Friction must be equal is quite restrictive. It is useful to extend Hess' notion to include other zero and non-zero values of friction and breakout, independently, and try to accommodate pilots' opinions of these two effects in a figure of merit.

Consider first the case of large Breakout and no Friction, illustrated in Figure 4-25. For this case, Hess' LI function would require computing of the Area(DABD) and Area(DBCD). The first term makes sense, since the index should penalize the presence of the large Breakout. But with no Friction, Points B and C are coincident. What to do with the return path for the no Friction case can be helped with consideration of the non-zero friction case, as in Figure 4-26, which is far more common in practice.

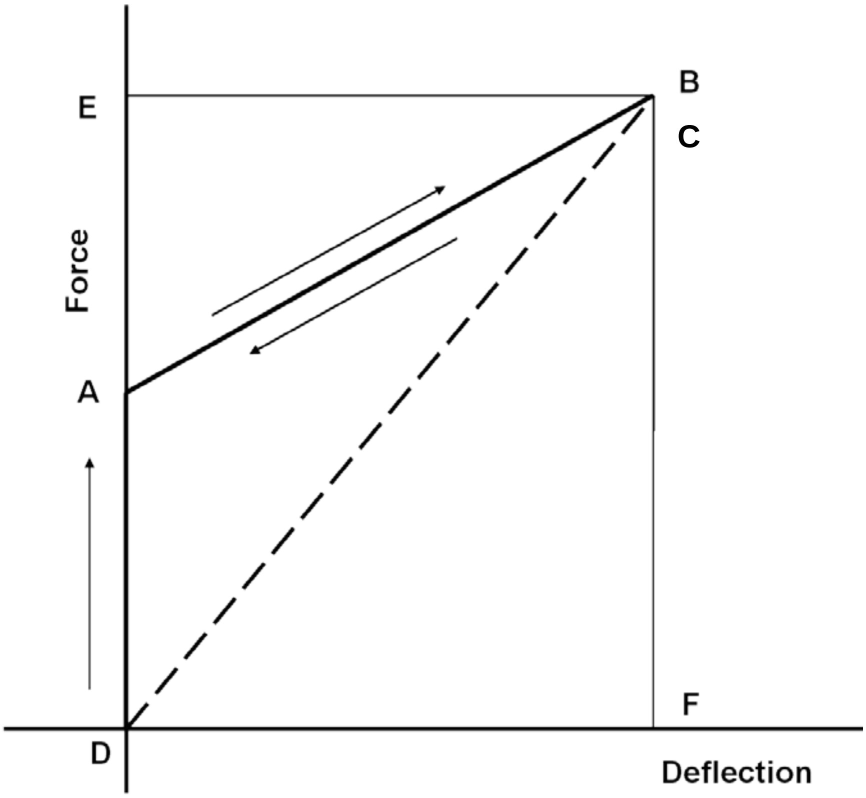

Figure 4-25. Large Breakout, Zero Friction

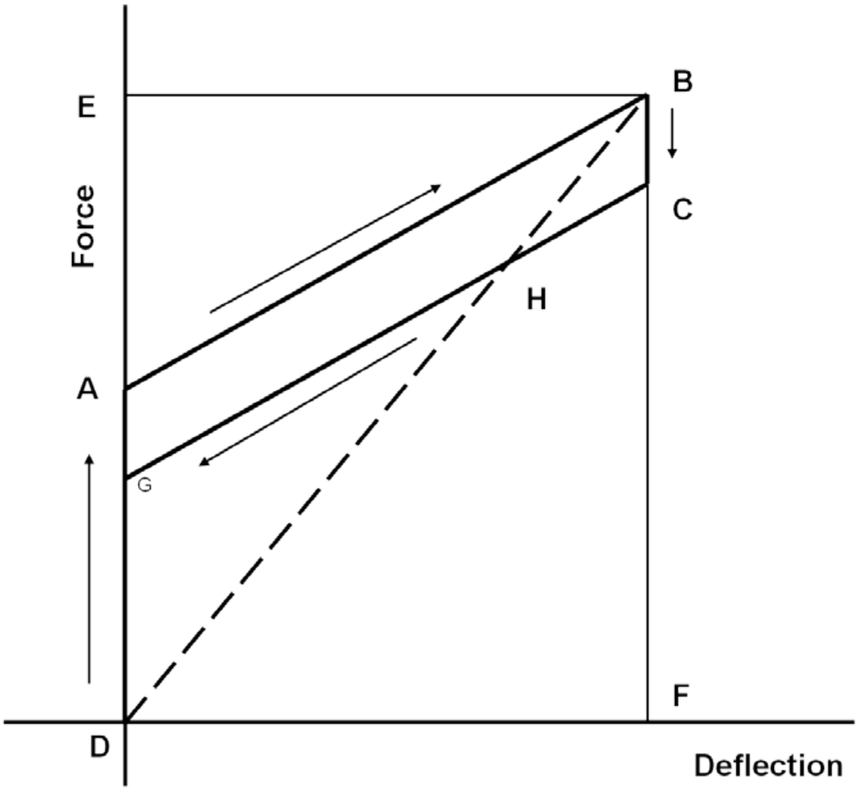

Figure 4-26 Large Breakout with Friction.

Two strategies are offered for consideration. In both of these, the outbound-from-neutral deflection is considered just as Hess suggests, Area(DABD). The first strategy involves recognition of the fact that it is the gradient ambiguity coming from the size of the friction band which generates difficulty on the part of the pilot. So this strategy is to simply add the area generated for the outbound path to the area of the friction band. Essentially, the effect of the return-to-neutral path becomes the size of the parallelogram it creates with the outbound path. It is recognized that this has the potential to result in negative Index values. This does not give rise for concern, as the physical condition which produces negative values is generally regarded as also producing poor pilot ratings.

In the second strategy, the return-to-neutral deflection will consider the deviation from linear for the return path. This amounts to computing and adding the areas of triangles BCH and HGD in Figure 4-26. In the limit at zero friction, this would produce a result numerically equal to the Friction = Breakout case of Hess. In the other limit of Friction = Breakout, the result is precisely that of Hess. The fact that both of these limit conditions produce the same value of LI is not bothersome, because pilots frequently give identical pilot ratings in different conditions for very different reasons. This is justified in the work reported in Lee, Rodchenko, and Zaichik, (2003). Moreover, there is evidence that pilots actually prefer a small amount of Friction, because it reduces the force precision required for them to hold the control away from neutral, thus reducing workload.

Whereas the Hess formulation was valid only for the case of Friction = Breakout, either of these new strategies can be used to evaluate “linearity” with both Friction and Breakout as independent variables.

Strategy 1

For the first strategy, the area of the triangle DAB is added to the area of the parallelogram ABDG, then normalized by (E*F), the total area of the rectangle.

This first Modified Linearity Index becomes then, in terms of the definitions given in Figure 4-26:

$$M1LI = 1 - \left[\frac{\frac{3}{2} Force(A) - Force(G)}{Force(E)} \right] \tag{4.24}$$

It is immediately clear that this Index responds to both the offset distance and the size of the friction band. It is equally clear that this Index is a function of the command gradient, but not of the total deflection, as was the case with Hess' one-dimensional formulation. In terms of physical values of Friction and Breakout, defined in Figure 4-27, Force(A) is Breakout + Friction, while Force(G) is Breakout – Friction. The first Modified Linearity Index becomes

$$M1LI = 1 - \left[\frac{(Br + 5Fr)}{2Fm} \right] \tag{4.25}$$

This Modified Linearity Index can then be fitted to a surface and contours plotted on a phase plane of Friction vs. Breakout, as in Figure 4-28. In Figure 4-28, both Friction and Breakout have been normalized with the same value. Figure 4-28 was computed for a single command gradient, which was selected as being typical of that used for lateral controls of large transport aircraft with wheel controllers. Of course, the Index values would change as a result of a pure gradient change, because the maximum force for each combination of Breakout and Friction would change, as seen in Equation (4.25).

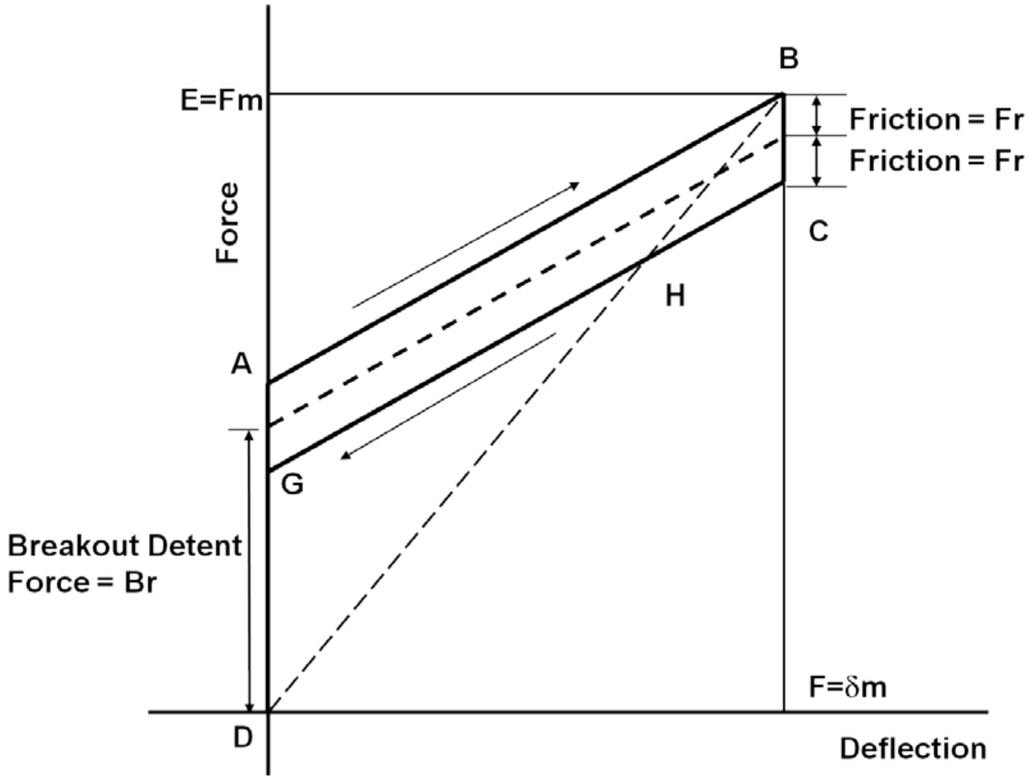

Figure 4-27. Dimensional Definitions.

Examination of Figure 4-28 indicates that this Linearity definition is more sensitive to Friction than to Breakout (also evident from equation 4.25). At first, this is not particularly interesting, but a closer examination reveals some interesting trends. At small Friction, the addition of Breakout leads to decreasing LI values. More interesting, at large Friction, the addition of Breakout leads to increasing LI values. These are both in line with the empirical observations made in the introductory discussion. At all values of Breakout, the addition of Friction degrades LI. This is also in line with the general comments about gradient ambiguity, but does not recognize the fact that pilots actually prefer a small amount of Friction, because it improves their ability to hold a particular control deflection without being quite so precise in the force they are holding.

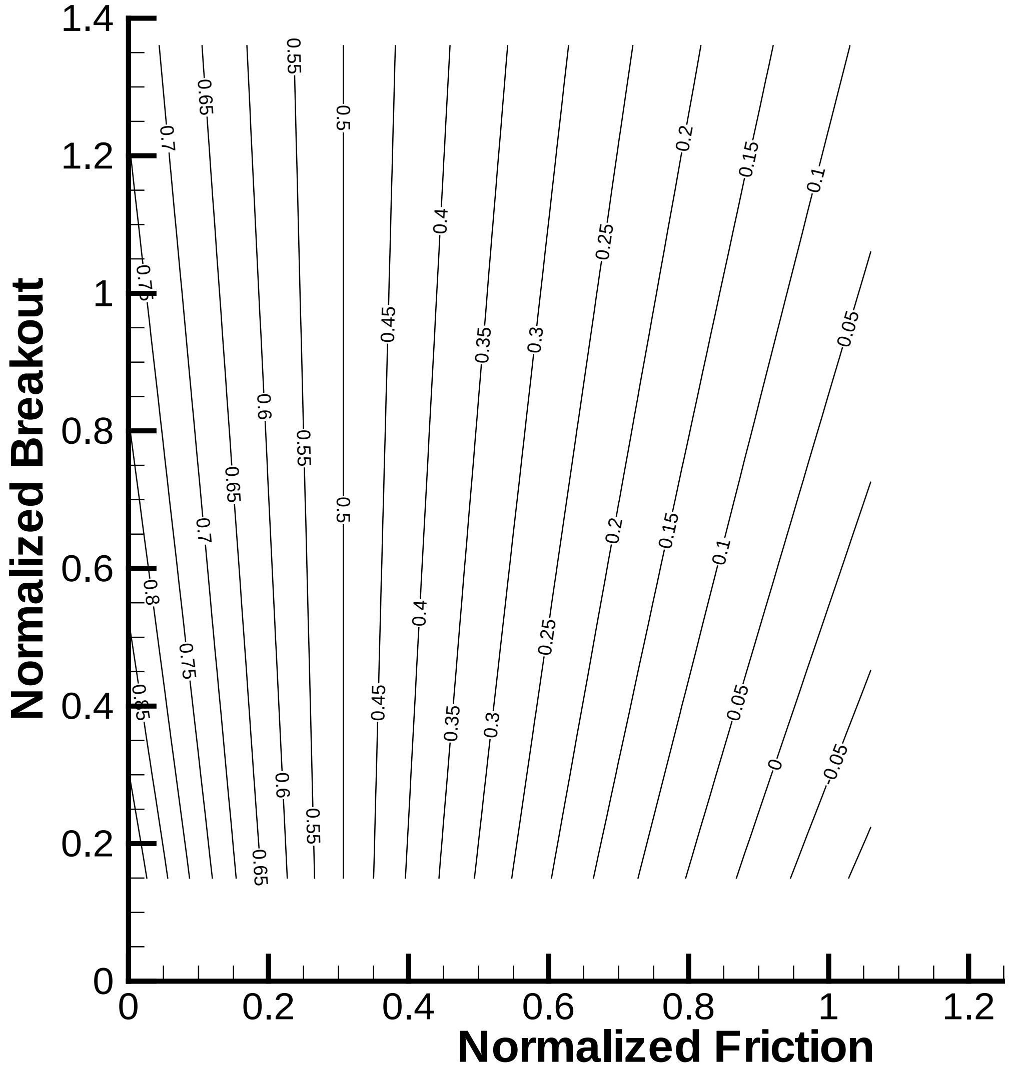

Figure 4-28. Iso-Linearity Contours, Strategy 1.

<u>Strategy 2</u>

In a purely geometric approach to this second strategy, the fundamental definition of the Linearity Index contains the area of the triangle DEBD for the outbound segment, and the two triangles BCH and HGD on the inbound segment. To compute the areas, it is first useful to cast the equation in non-dimensional terms, illustrated in Figure 4-29. There, A is the outbound y-axis intercept, G is the return-path y-axis intercept, and m is the command gradient for both paths. Then, it can be shown that this Second Modified Linearity Index becomes:

$$M2LI = 1 - \left[A - \frac{(1-m)}{2} + \frac{(1-m)^2 - 2G(1-m) + 2G^2}{2(1-m)} \right] \quad (4.26)$$

In the limiting condition when G = A, the return path term on the right hand side inside the brackets is just the same as the outbound-path term, which is represented by the first and second terms. In this case, the numerical value of the Index is the same as Hess' Friction = Breakout case. Similarly, for the limiting condition at G=0, the terms are again equal, producing the same numerical value as Hess got for the case of Breakout = Friction. There is a difference in between, however. Unlike the form of Strategy 1 above, this formulation actually produces an improvement (numerical increase) in the Index value for small additions of Friction to a large Breakout case. This characteristic is not unlike the changes in pilot opinion in the same case.

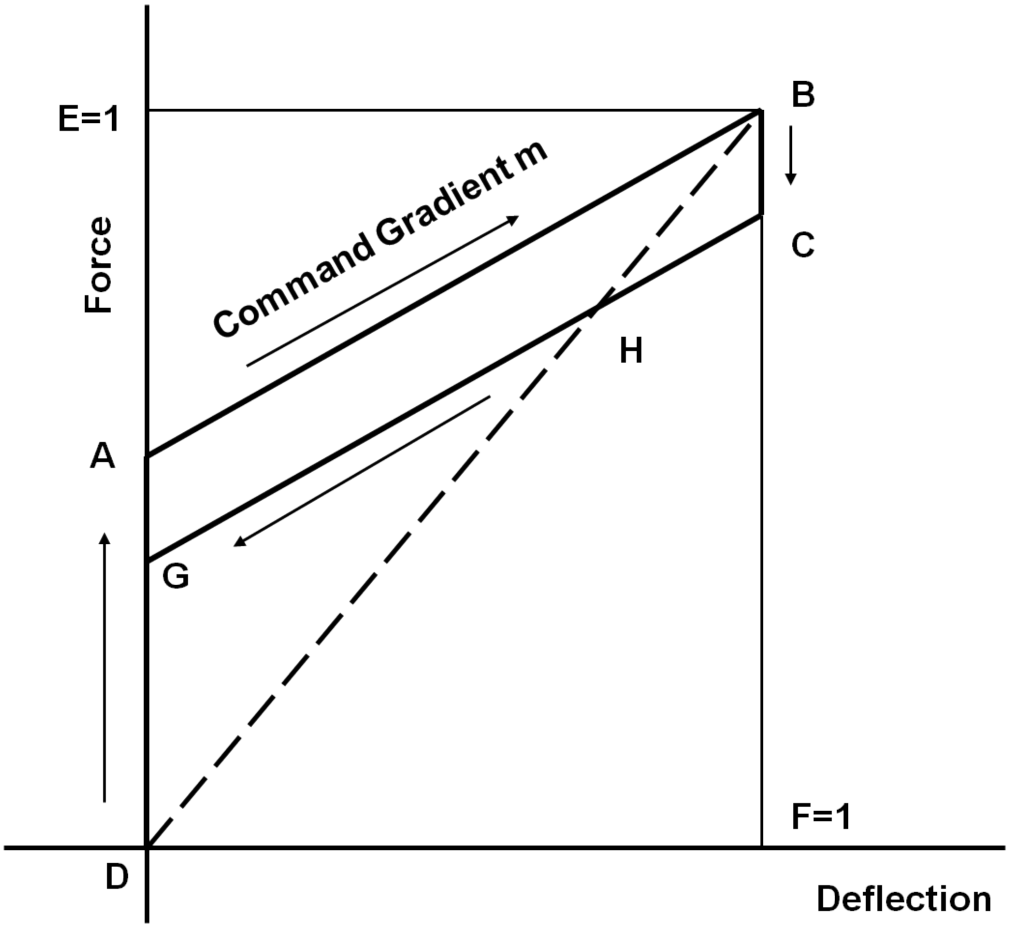

Figure 4-29 Nondimensional Definitions.

In terms of the dimensional parameters of Figure 4-27,

$$M2LI = 1 - \left[\frac{\frac{(Br+Fr)}{2} + \frac{(Br-Fr)^2}{2(Br+Fr)} + \left[\frac{(Br+Fr)}{2} - (Br-Fr) + \frac{(Br-Fr)^2}{2(Br+Fr)} \right]}{Fm} \right] \quad (4.27)$$

for Breakout > Friction. For the case of Friction > Breakout, the triangle HGD has zero area, and the area BCH becomes non-triangular, because deflections less than zero are not considered. For those cases, the Index becomes

$$M2LI = 1 - \left[\frac{\frac{(Br+Fr)}{2} + \frac{(Br+Fr)}{2} - (Br-Fr)}{Fm} \right] \quad (4.28)$$

These can similarly be fitted with a surface and contours plotted on the phase plane of normalized Breakout vs. Normalized Friction, as in Figure 4-30.

Again, this was computed for a command gradient typical of large jet transport aircraft.

The results of Figure 4-30 are much more interesting. Here, at all but the lowest levels of Friction, the addition of Breakout first improves, then degrades the index (this is consistent with a centring requirement). At all levels of Breakout, the addition of Friction at first improves, then degrades the index, in contrast to the results of Strategy 1.

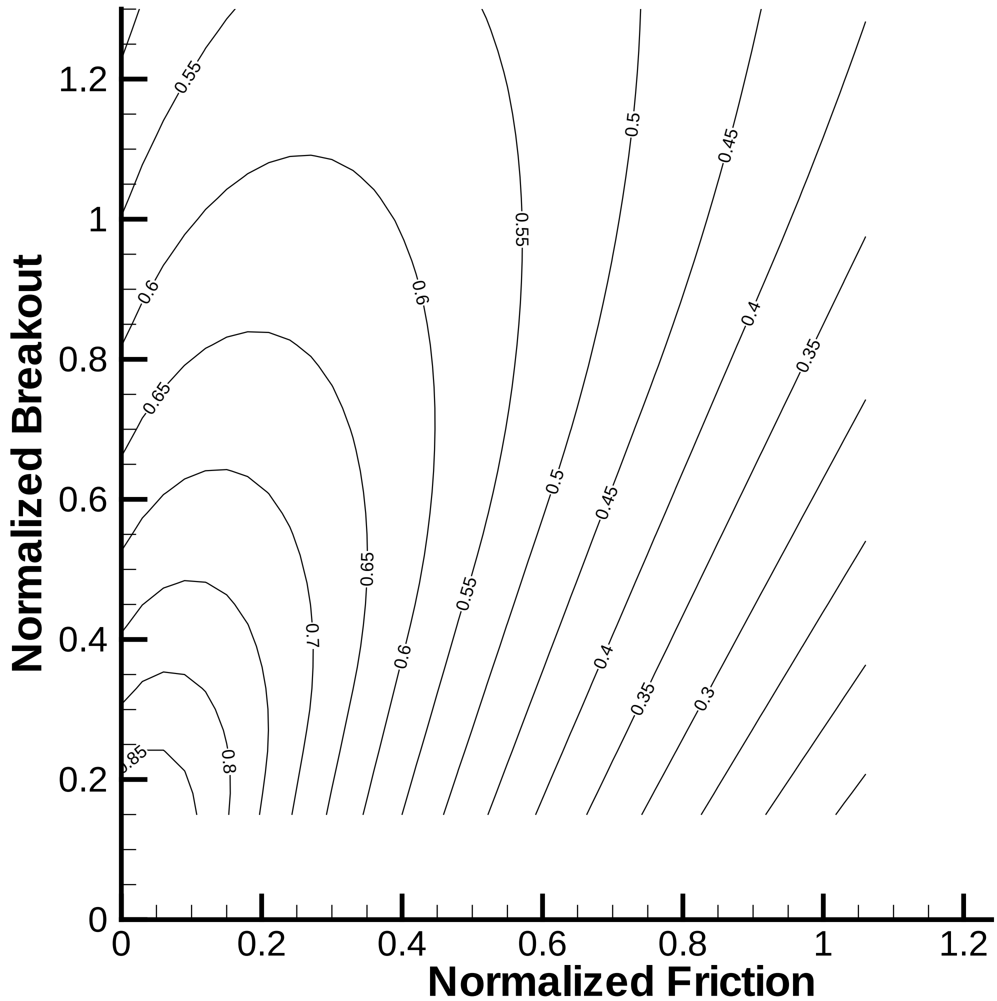

Figure 4-30. Iso-Linearity Contours; Normalized Gradient =1.0

As was done for the Hess formulation, the Modified Linearity Index (Strategy 2) can now be evaluated for various parameter changes. First, the effects of changing the command gradient can be computed and plotted on the same map, as in Figures 4-31 and 4-32. Comparing these with Figure 4-30 and with each other, it is clear that the shape of the iso-Linearity contours is not appreciably changed but the values for each combination of Friction and Breakout are significantly different as the command gradient is changed. As with the Hess formulation, this effect is a result of the properties of the area of a parallelogram.

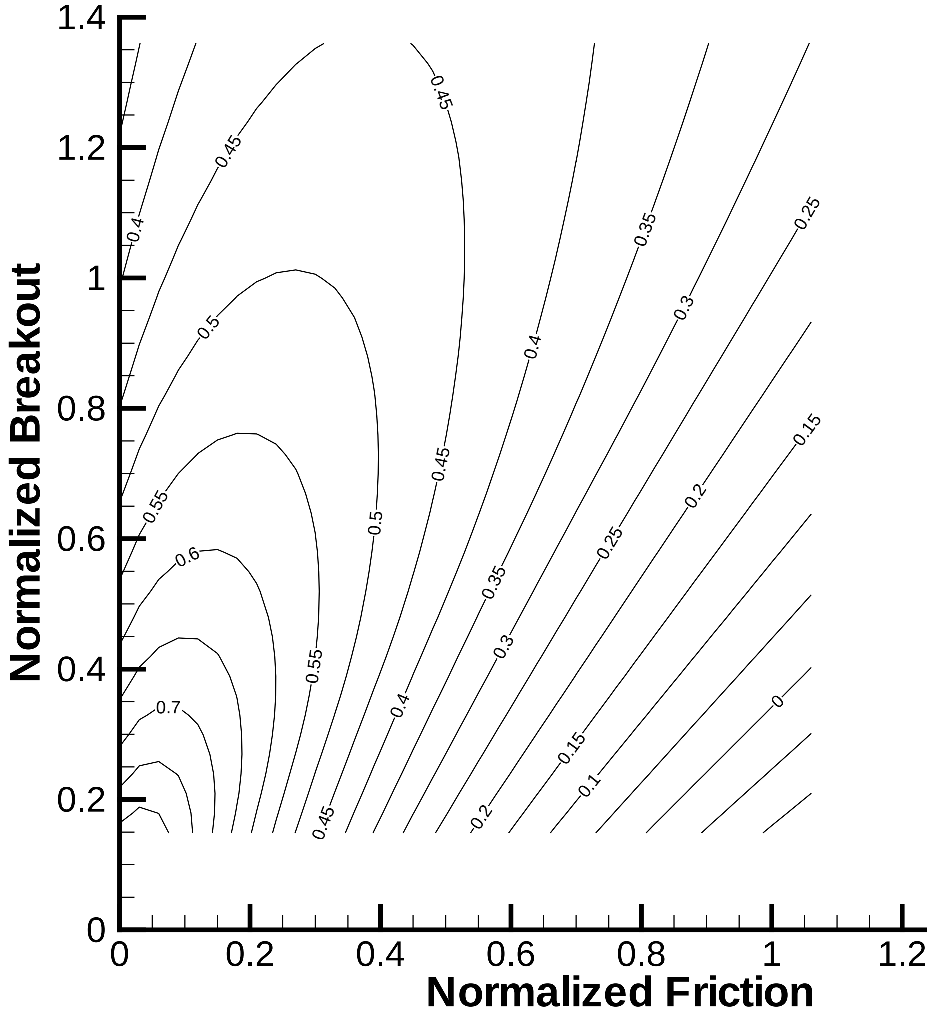

Figure 4-31. Iso-Linearity Contours; Normalized Gradient = 0.54

Similarly, the effect of changing the maximum deflection can be found, as illustrated in Figure 4-33.

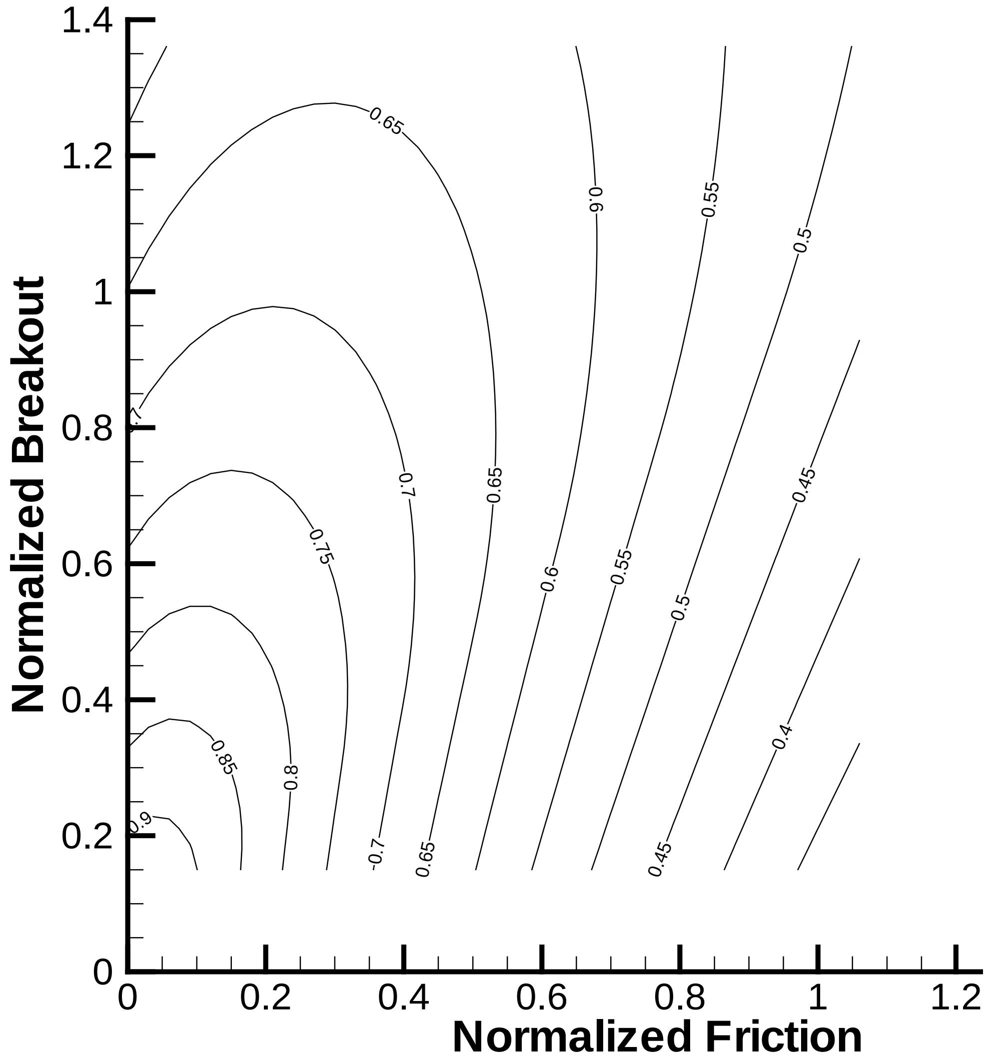

Figure 4-32. Iso-Linearity Contours; Normalized Gradient = 1.5

Comparing this to Figure 4-30, it is at once clear that the iso-Linearity contours are identical for both cases. While Strategy 2 has succeeded in generating a figure of merit for classifying linearity, it is still a geometry-based approach which suffers the same limitations as Hess's original formulation.

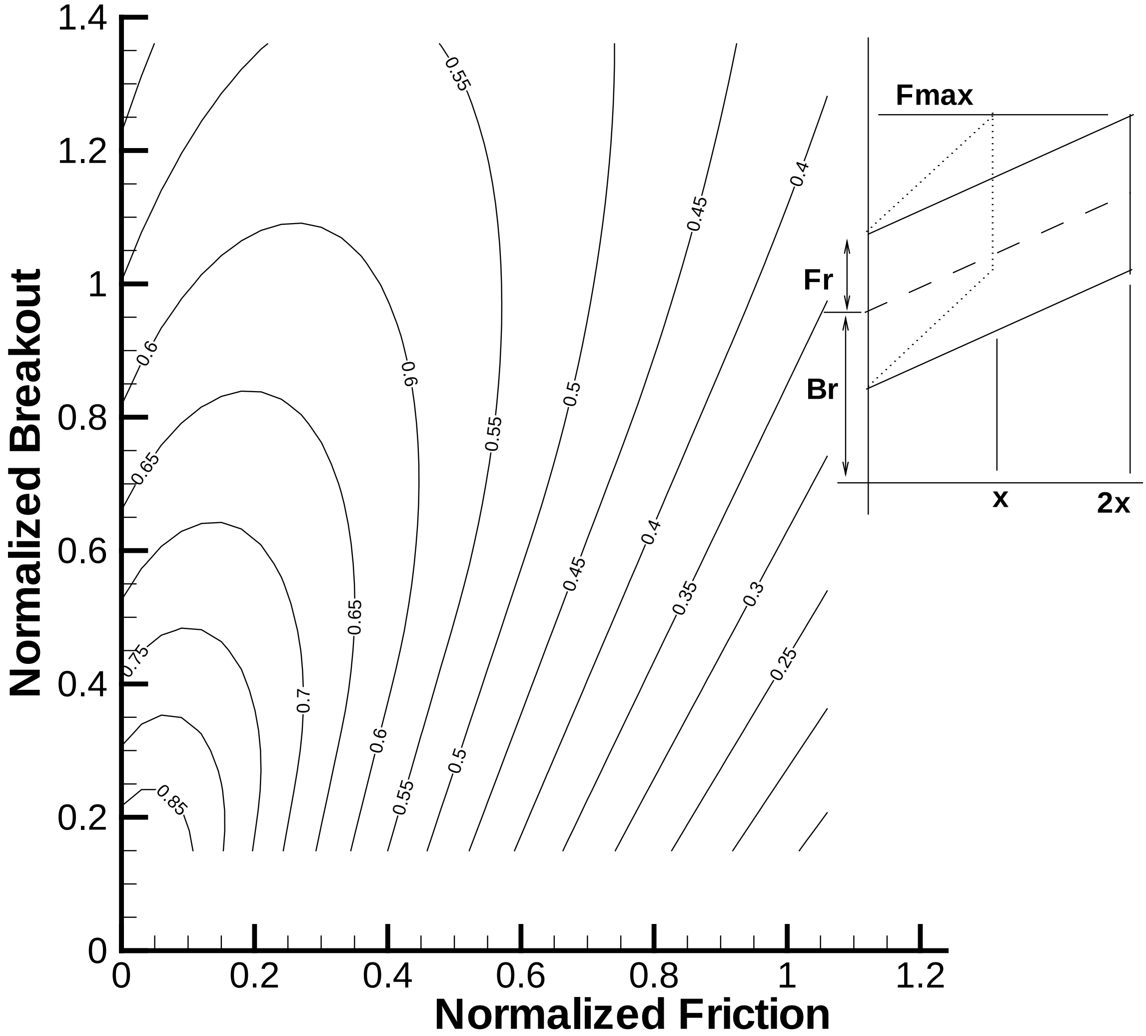

Figure 4-33. Iso-Linearity Contours.
Max Deflection =2x of Fig. 4-30.

Application

Regardless of the limitations of the geometric method, it is still interesting to see how the results of this measure of linearity compare to pilot opinion results. The method of Strategy 2 above has been applied to a geometric case typical of the control wheel of a large jet transport, with a typical command force gradient, and typical maximum deflection limits for which pilot opinion data were available. The Modified Linearity Index of Strategy 2 was computed for a range of Breakout and Friction values, fitted to a surface, and the iso-Linearity contours computed. These were then overlaid with the Level 1 and Level 2

Pilot Rating boundaries computed from the methods of Lee, Rodchenko, Zaichik, (2004). The results are plotted in Figure 4-34.

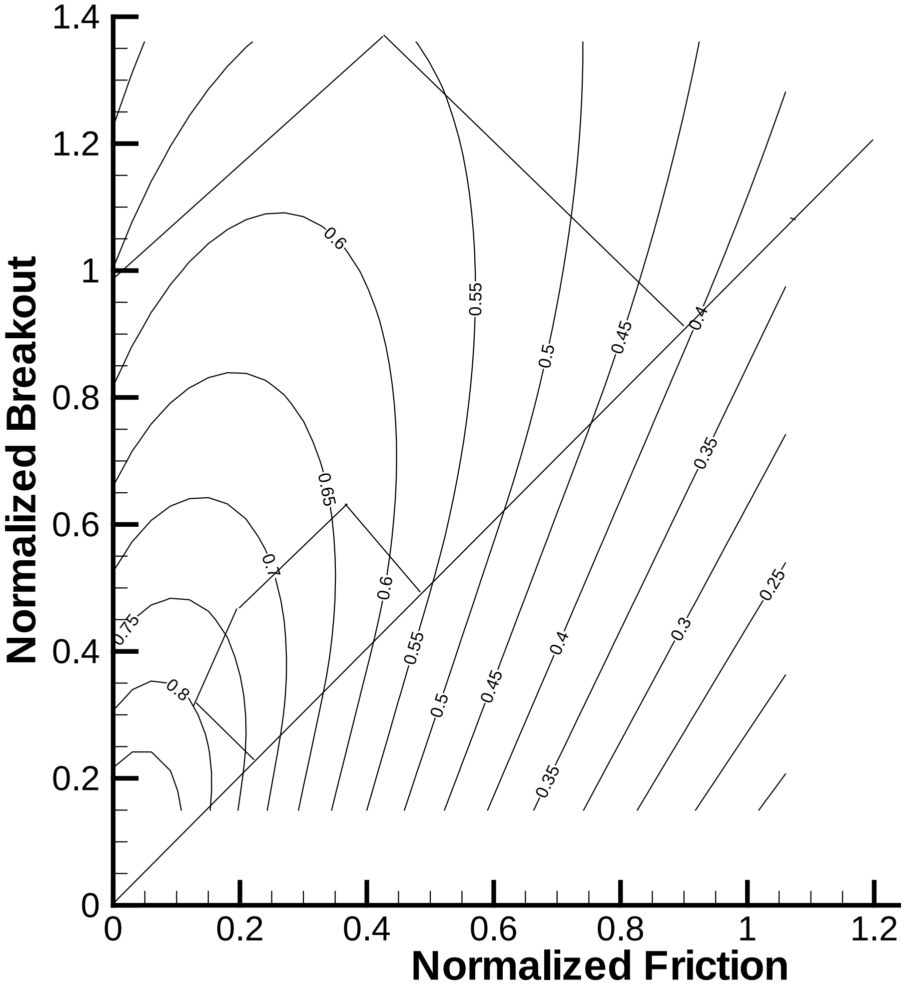

Figure 4-34 Iso-Linearity Contours Compared to Results from Lee, Rodchenko, and Zaichik (2004)

It is clear that as an indicator of Handling Qualities, the Modified Linearity Index alone is not sufficient. It does, however give some interesting indications. For example, there is a significant area of the region bounded by MLI values greater than 0.55 which is also bounded by the Level 2/3 boundary found from piloted evaluations, particularly if only the combinations of Breakout and Friction which produce positive centring are considered (Br>Fr).

The smaller area bounded by the Level ½ boundary is not so conveniently lined up with iso-Linearity contours, but nevertheless, there is certainly a range of MLI values which are not acceptable. This is one useful application of a figure of merit: very quick classification of regions. As Hess noted, small values of Linearity Index are to be avoided.

4.2.4 Summary of Pilot Manipulator Feel Investigations

Experiments were conducted to evaluate minimum resolution in the pilot's ability to manipulate a transport aircraft wheel controller. In general, pilots could generate increments of 0.5 degrees with force increments of 0.5 lbs. Unfortunately, the pilots adopted a technique which was not intended. Instead of steadily increasing the force level until a new deflection had been achieved, they used an impulse to "bump" the wheel to a new position. This they demonstrated that they could replicate quite accurately.

A theoretical method was developed to estimate optimum combinations of feel system parameters. Comparison with the measured boundaries produced a good correlation.

Experiments were also conducted to determine handling qualities directly as a function of feel system parameters for landing tasks with a wheel controller in a large transport.

Two extensions to Hess's Linearity Index were attempted to remove the limitation that friction be equal to breakout in his original version. These extensions were evaluated against results of the handling qualities evaluations conducted in the simulation experiments with the conclusion that while these extensions could identify negative effects of excessive breakout, neither correlated well with measured results: iso linearity lines did not correlate well with iso-handling qualities lines.

4.3 Measuring Feel System Effects on Human Pilot Dynamics

4.3.1 Introduction

Many people have extracted pilot frequency response functions from tracking tasks using apparatus and models ranging from quite simple to very sophisticated. Some, like McRuer's seminal work (e.g. McRuer,1965) was focused on understanding the pilot's interaction with the flight dynamics of the rigid body, across a wide variety of controlled element structures. Some were focused on understanding the details of human body functions as sensors and actuators (e.g. Hosman (1996), vanPaassen(1994)). Very little work has been done to look at how the pilot deals with the details of the manipulator for wheel/column in a large transport airplane. The emphasis in the current work is to use the mathematical descriptions of how the pilot interacts with the airplane controls to inform details of the cockpit feel; to give physical understanding to why the pilot's comments reflect preference for some characteristics and not others.

4.3.2 Philosophical Approach

Having evaluated the work of others in Chapter 3, it was decided to propose a two-loop model of the pilot: an inner loop between the pilot and the feel system (the limb-manipulator) and an outer loop involving the pilot and the airplane dynamics in the tracking task. A block diagram of this construct is shown in Figure 4-35.

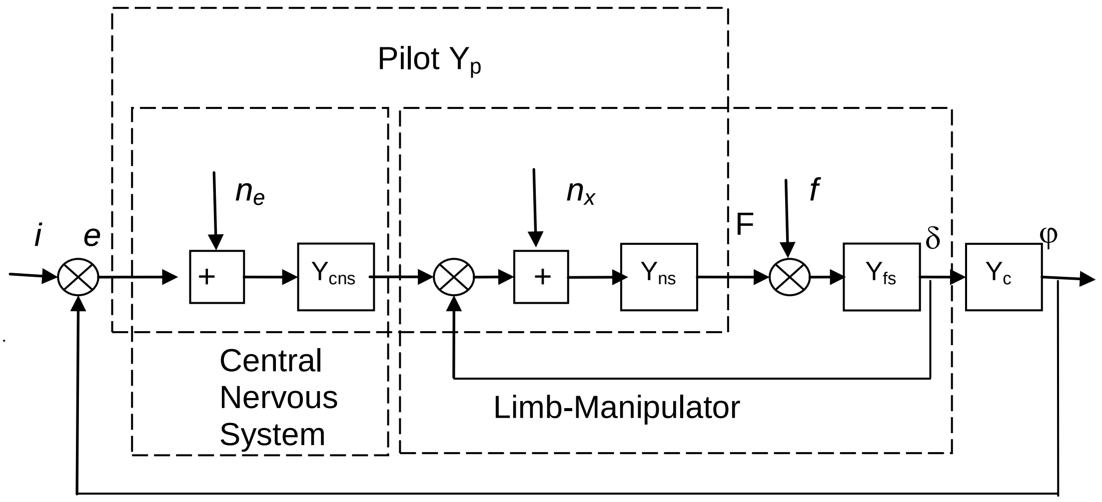

Figure 4-35. Assumed Pilot Model Structure

Beginning at the inner limb-manipulator loop, the output of the neuro-muscular system, Y_{ns} is the force F that the pilot wants to apply to the wheel based on the pilot's attempt to close the outer loop. This force is added to the disturbance force *f* which is then an input to the feel system. With that force input, the feel system generates a deflection δ to the controlled element generating a bank angle φ. The difference between this actual bank angle and the commanded bank angle i generates an input to the Central Nervous System, Y_{cns}. The output of the Central Nervous System can be considered to be the "intended wheel position" based on the error signal input. This then is summed with the actual feel position and the error is an input to the neuro-muscular system. In this structure, the n_e and n_x inputs represent the nonlinear remnants of the pilot model; those responses which are not linearly correlated with the inputs. These will be considered to be small.

One of the considerations which makes this a particularly challenging problem is that there are two loop closures involved. In order to identify describing functions for both loops simultaneously, two disturbance functions are required. While the pilot is tracking the input *i*, there is an additional disturbance function *f* being input just upstream of the feel system. In practice, this function *f* is seen to "jerk the wheel around" or "pull the wheel out of the pilot's hand" while the pilot is visually tracking the input signal *i*. This feature, found annoying by the pilots required careful tuning in amplitude. It needed to be large enough to be identifiable and at the same time allow the pilot to fly the task.

Another other consideration which made this challenging was that in order to do the identification of both loop closures simultaneously, the two input signals needed to be completely uncorrelated. Finding two entirely independent multi-sine functions which cover roughly the same frequency range was a challenge.

Another aspect of this assumed model posed a challenge was the loop closure around the feel system. It seemed obvious that the limb-manipulator system needed to be evaluated, but it did not make sense to suggest that the feel system should be considered part of the pilot. In the present case, the characteristics of the feel system would be known, so it was decided to construct a loop closure for the neuro-muscular system and the feel system resulting in a model of the limb-manipulator, only part of which resides in the pilot model. Thus the overlapping boxes depicted in Figure 4-35.

Finally, all of the previous modelling work reported in the literature and reviewed in Chapter 3 dealt with only linear feel system characteristics. In fact, it has been typical to deliberately eliminate nonlinear elements altogether in both research experiments and in analyses. In this work, one of the motivations was to look specifically at the nonlinear feel system elements. The measurement of frequency response functions does not require a linear system or a nonlinear model. Graham and McRuer (1961) argue that the control loop itself provides sometimes significant linearization of the signals. In this case, it will be sufficient to observe the changes in the linear(ized) system description to variations in the nonlinear feel system elements. This complements the experimental work reported in Section 4.2 in which pilot opinion was collected in the presence of these nonlinear elements. The data of this section explain what changes to feel system characteristics do to the character of the pilot's loop closure; the pilot opinion data of Section 4.2 explains whether those changes which show up in the describing functions make it easy or difficult for the pilot to manoeuvre the airplane.

4.3.3 The Experiments

Data were collected during closed loop compensatory tracking tasks in the roll axis of a simulated large transport aircraft, using a motion-base simulator. Three experienced professional test pilots participated in the experiments. Elements of the experiments were as follows.

The Simulator

The experiments were conducted in a transport aircraft research simulator equipped with a wheel-column controller driven by high fidelity electric control loading which allowed the entire range of feel characteristics to be replicated faithfully. The cockpit has 4-window collimated visual display and electronic flight displays. The tracking task was implemented on a research electronic primary flight display using the flight director bars for displaying tracking commands. The normally heavily filtered flight director commands were bypassed to reduce the display delay to an absolute minimum.

Experiments were conducted both motion on and motion off. The motion system is a 6 degree of freedom hexapod with actuator stroke of ~2 meters. The amplitudes of the driving signal and the motion system washout filters were of standard architecture, but were tuned to provide the pilot with the most representative motion cueing possible for this lateral-directional task.

The Simulated Aircraft / Flight Condition

The simulation model for these experiments was a generic research configuration representing a wide-body commercial airliner. Care was taken to ensure that it represented neither the light weight nor the heaviest weights seen in the service fleet today. The simulated airplane was flown at a weight of ~473,000 lbs.

Dutch roll damping was Level 1 and control power was representative of current fly-by-wire aircraft. Roll mode time constant was varied during the testing. Lateral wheel deflection was approximately +/- 6 inches. The longitudinal control system characteristics were constant and represented a typical wide-body twin in terms of control power and sensitivity.

The condition flown was level flight at a mid CG and at a speed representative of a landing approach at maximum landing weight (roughly 140 knots). This low speed flight condition was chosen because it is in the terminal area manoeuvring that one would expect to see the biggest need for precise flight path (in this case lateral path) control and the most active continuous piloting tasks.

The Configuration Variations

During the conduct of the study, several parameters were varied in order to generate comparison data and to look for trends in the extracted results. Those parameters chosen for the study are given in Table 4-6

Parameter	Values			
Wheel System Mass slugs	0.1	0.17	0.26	0.49
Spring Gradient Lb/in	0.	1.16	2.28	4.56
Friction Lb	0.	3.3	6.1	
Breakout Lb	0	2.5	4.0	
Damping Lb/In/s	0.	0.15	0.25	
Roll Mode Time Constant sec	0.7	0.9		

Table 4-6 Control System Configurations

Not every pilot flew every configuration. Not every combination of configurations was flown. More than 60 combinations were flown. Each pilot who flew a configuration flew it 3 times for data consistency.

The Manoeuvre / Task

The primary tool for this experiment was the compensatory tracking task, illustrated in Figure 4-36. In this case, the pilot was dealing with two control loops simultaneously: the outer loop, controlling an input *i(t)*, and in the inner loop for wheel position, the pilot had to deal with a disturbance input *f(t)* while tracking. Each condition was evaluated 3 times.

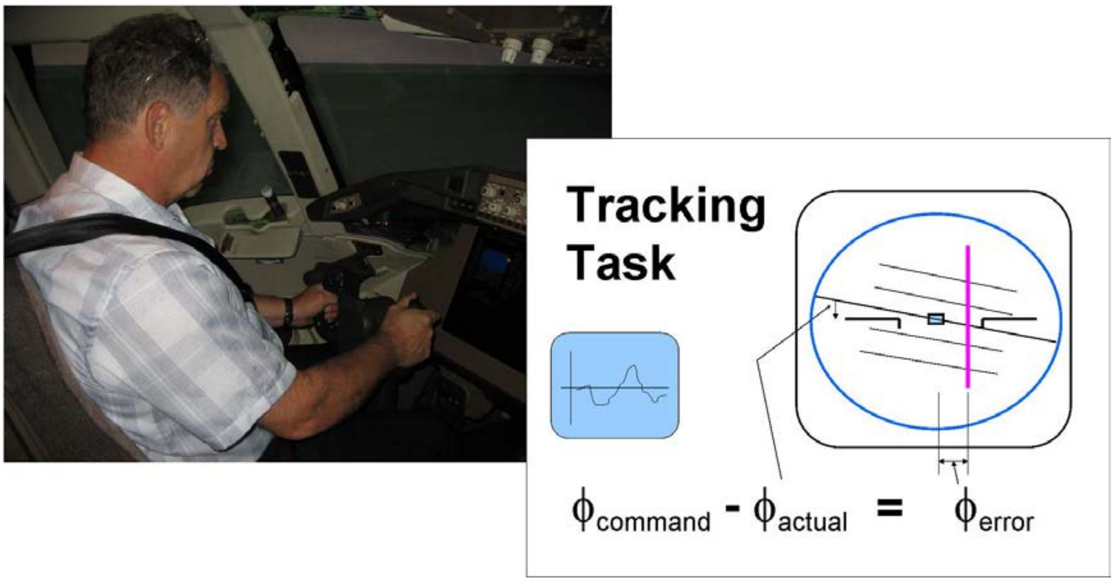

Figure 4-36. Compensatory Tracking Task
(Photo courtesy of Boeing)

As shown in the figure, in a compensatory tracking task the pilot does not see the actual command signal. What is displayed on the pilot's Primary Flight Display (PFD) is only the error between the command and the actual bank angle at any point in time. By constructing the task in this way the pilot can only respond to the visual error. There is no way for a pilot to get a preview or to apply a pursuit strategy or an open loop pre-cognitive strategy. This is done to force the pilot to the most fundamental of McRuer's SOP strategies, which has the effect of equalizing the pilot population with regard to learned responses. It also provides a more conservative answer: if a pilot in a non-test environment can use a learned response, or take advantage of a pursuit strategy, he may be able to achieve even better performance.

Figure 4-37 Pilot’s Simulator Display for Flight Director Tracking
Photo Courtesy of Boeing

In this test, the error was shown on the pilot’s primary display as a flight director command, using a display similar to a Split Cue flight director. The generic display used is shown in Figure 4-37. On this display, the magenta cross-hairs (the split cues, one for pitch, one for roll), command the pilot to change the attitude. The pilot will manipulate the control in an attempt to put the airplane attitude symbol (the small white box in the centre) on the intersection of the magenta crosshairs. In the figure, the airplane is at ~2.5 degrees nose up and 10 degrees bank to the right. The flight director is commanding a pitch up and a bank to the left. Note that this roll command is only displaying the error, so the “bank Left” command might not mean “establish Left wing down”, it only means “bank more Left than you are now”.

The approach taken to analyze the two-loop pilot model in which two uncorrelated forcing functions are used was proposed by Rodchenko, et. al. (1996). In order to identify the describing function of the limb-manipulator system, the system has to be isolated in the pilot model structure. The purpose of the neuromuscular system in this context is to transfer the control forces to the manipulator. That is why the second controlled parameter, which is the force generated by the neuromuscular system to perform the manipulator displacement according to the input from the central nervous system is identified (Figure 4-35).

In order to invoke a Fourier transform method to extract the two describing functions and the remnant, it is necessary to find two uncorrelated forcing functions. In general, preferred forcing functions consist of sums of sines as

$$i(t) = \sum_{i=1}^{m} A_i \sin \omega_i t \,, \tag{4.29}$$

Where ω_i is to satisfy the condition $\omega_i = n_i \omega_0$, $\omega_0 = \frac{2\pi}{T}$, where n_i is an integer, T is the time interval over which the recordings are being carried out.

For the two-loop task, another forcing function, $f(t)$ is used;

$$f(t) = \sum_{f=1}^{m} A_f \sin \omega_f t \,. \tag{4.30}$$

Having two forcing functions, each generating an uncorrelated polyharmonic input within the same time frame T is difficult. One solution is selection of harmonics in each of the inputs in such a way that no harmonic of one input is divisible by the harmonic of the other.

The number of harmonics in each signal must be large enough to make the input signals appear unpredictable for the pilot and to make them as similar to those in real flight as possible. For a polyharmonic input the amplitude distribution approaches a Gaussian distribution for m>3.

The larger number of the harmonics in the input, the larger the number of magnitudes and phases are in the describing function and its remnant. However, as the number of harmonics increases, the accuracy of the describing function identification decreases. Experience shows that 10-15 are sufficient to get a rather complete description. This experiment used 14 harmonics.

Once the condition began, the driving algorithms ran for 210 seconds. That works to two times the lowest frequency in the driving signal (to ensure data quality) plus 10 seconds. The 10 seconds served as a “warm up” for the pilot, to try to establish a “stationary” tracking solution.

4.3.4 Data Analysis

Once the recorded data have been processed, the Fourier transformations of the relevant signals are, unfortunately, at different frequencies (ω_i and ω_f). The results are then interpolated to intermediate frequencies to continue the analysis. These were selected to be between the relevant ω_i and ω_f. This yielded a set of describing functions for each condition flown.

The analysis of this measured data proceeded from this point through three stages. The first stage was, to analyze the frequency responses themselves. This was to arrive at conclusions regarding regularities of the changes seen in the frequency responses as the feel system parameters were changed. As an example of this process, Figure 4-38 shows the describing functions extracted for the limb-manipulator model in a particular condition. There are two Bode plots in the figure. The upper Bode plot shows the closed loop limb-manipulator performance for this particular condition (three runs). Since the configuration of the feel system was known, extraction of a description of the open-loop neuro-muscular system characteristics for these three runs is possible. This is shown in the lower Bode plot in the figure. One characteristic “signature” or “feature” of these extractions is what has been called “Neuro-muscular Dip”. This feature is seen in the amplitude Bode for the neuro-muscular system. From a “shelf” at approximately -60 dB, the neuro-muscular system amplitude “dips” before increasing again.

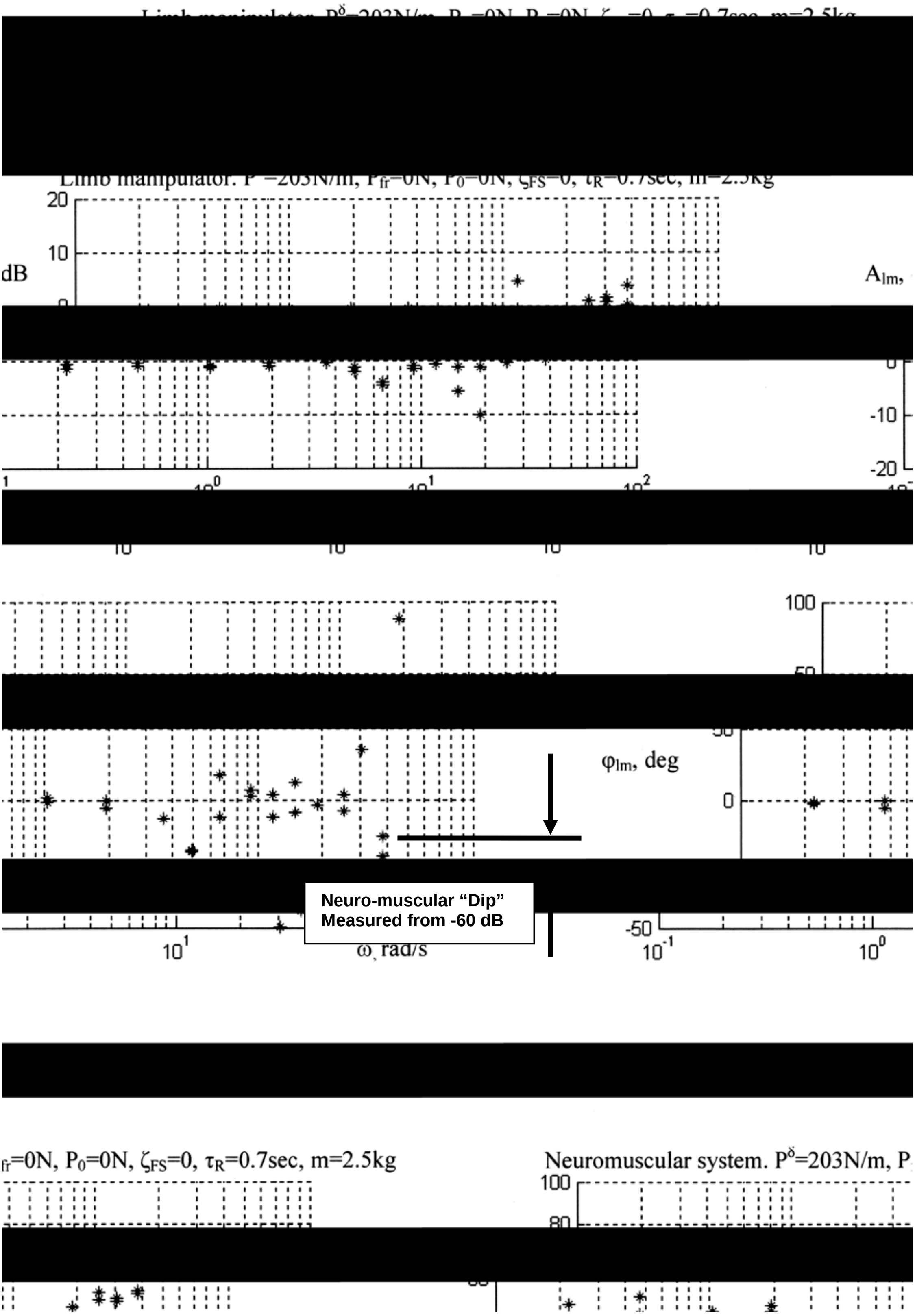

Figure 4-38 Definition of Neuro-muscular “Dip”

This feature is seen in all of the conditions, and “moves around” in centre frequency and gets deeper or shallower as a function of the feel system characteristics employed at the time.

The second step was to derive transfer functions which represented those frequency responses. The third step is to derive functions by which to adjust the parameters of the transfer functions as functions of the feel system changes.

This three-stage process progressed from the inner loop to the outer loop. Since the characteristics of the feel system for each configuration were known, the process began with the neuro-muscular system Y_{ns} and the closed-loop limb-manipulator system. Next in this progression was to evaluate the Central Nervous System Y_{cns} and finally to the pilot model as a whole, to understand any regularities as a function of changes to the feel.

4.3.5 Results and Findings

The effect of changing the spring gradient shows that as the gradient changes, the frequency ω_{ns} and the value of the “dip” Δ_{ns} in the neuromuscular system Y_{ns} change noticeably. There are also changes in gain Kns. Results for ω_{ns} and Δ_{ns} are given in Figure 4-39 and 4-40. Increasing the force gradient leads to a decrease in the frequency ω_{nns} and an increase in the “dip” Δ_{ns}. As the force gradient increases, the dip in Yns shifts to the left and its value increases. At the same time, the neuromuscular frequency ω_{ns} decreases by half, and the depth of the “dip” increases by 18 db (i.e. by a factor of nearly 8).

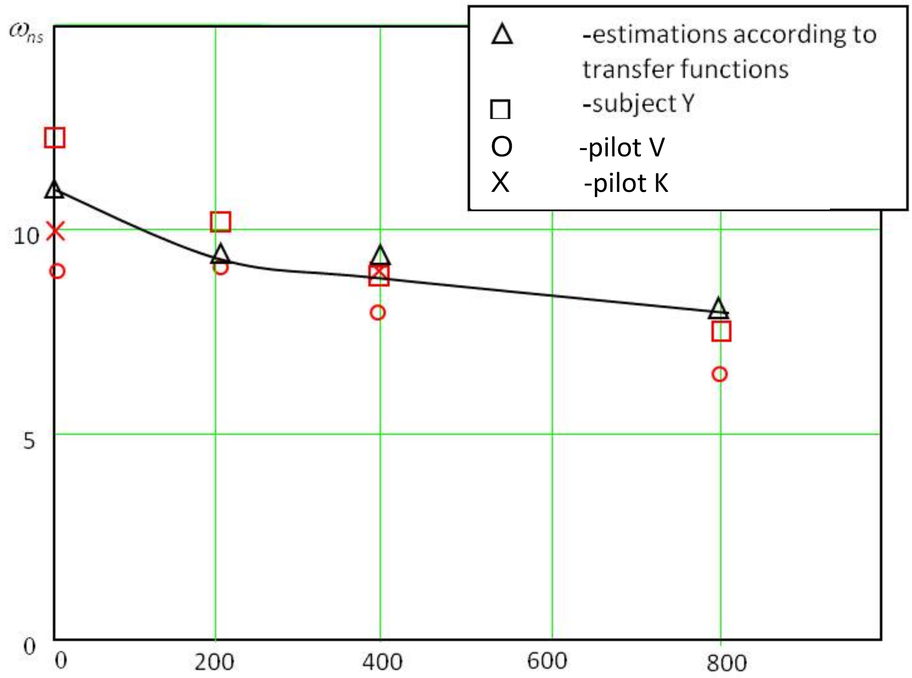

Figure 4-39. Reduction in Neuromuscular Frequency with Spring Gradient

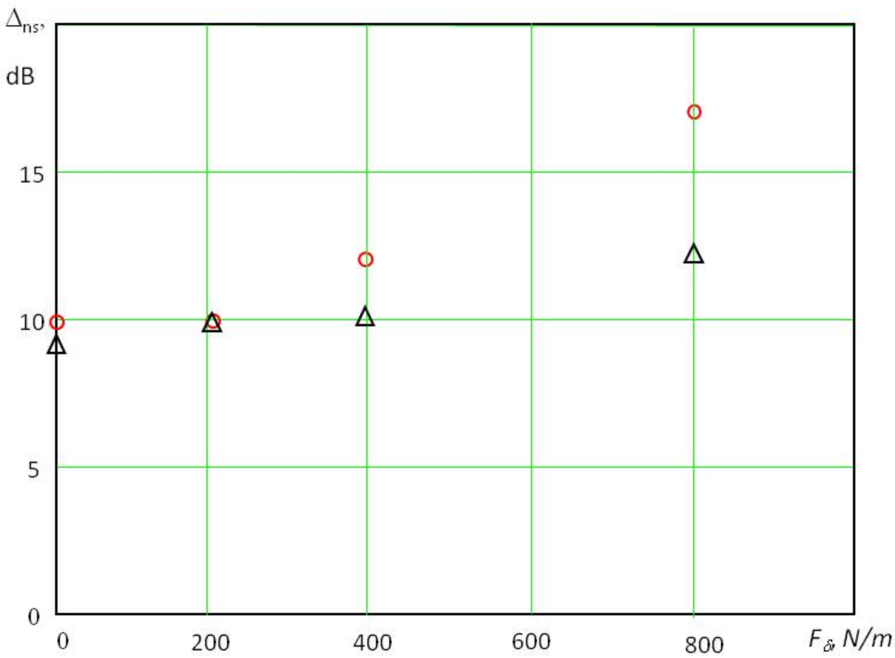

Figure 4-40. Effect of Spring Gradient on Neuromuscular "dip"

In terms of the limb-manipulator, Y_{lm}, there are changes in the crossover frequency, gain, and location of the magnitude minimum. The crossover frequency of the limb-manipulator open loop system as a function of the force gradient is presented in Figure 4-41.

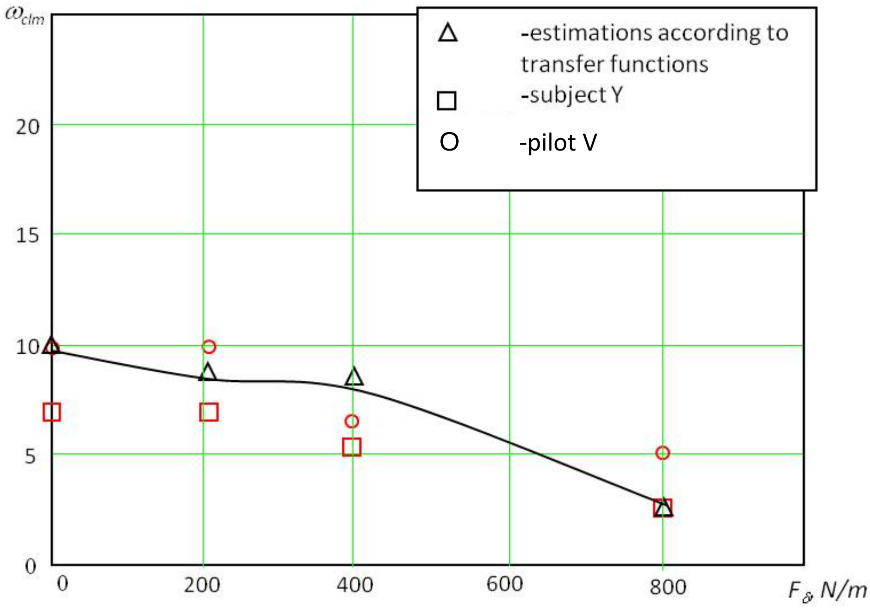

Figure 4-41. Effect of Spring Gradient on Limb-Manipulator crossover.

Finally, the limb-manipulator stability margins at those crossover frequencies are shown in Figure 4-42. That they are quite large testifies to the good limb-manipulator closed-loop stability for all values of force gradients considered in these experiments.

Description of the Neuromuscular system

The data analyzed is sufficient to generate and validate a transfer function describing the neuromuscular system (in conjunction with the feel system model and the central nervous system model). The model is of the form:

$$Y_{ns}(s) = K_{ns} e^{-\tau_{ns} s} \frac{[T_{ns2} s + 1][T_{ns3} s + 1][s^2 + 2\zeta_{ns}\omega_{ns} s + \omega_{ns}{}^2]}{[T_{ns1} s + 1]\omega_{ns}{}^2} \qquad (4.31)$$

and the necessary variations in parameters have been identified to cover the range of configurations tested. Importantly, for the range of feel system characteristics “typical” of transport aircraft, this model does not change much. On the other hand, at very small forces or very large forces, dramatic changes in these transfer function parameters were seen, suggesting that pilots can adapt readily to moderate differences in feel system parameter values, but it takes more effort when the system deviates from the norm.

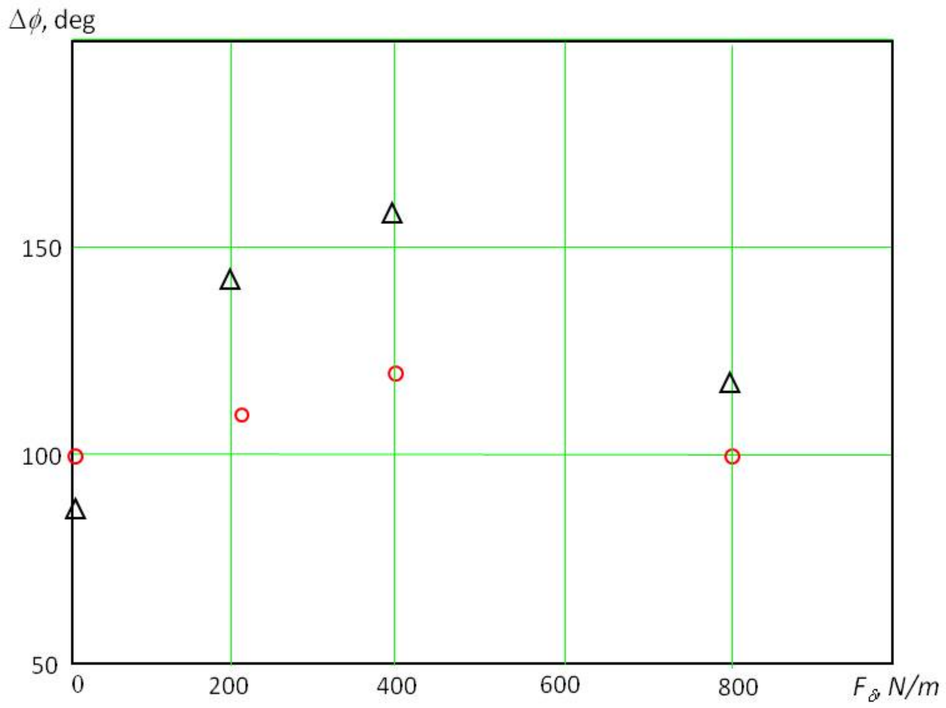

Figure 4-42. Limb-Manipulator Stability Margins for Gradient Changes

In addition, the nonlinear effects of friction and breakout force were also evaluated, and transfer function parameters were found for those characteristics as well. Briefly, nominal values of friction and breakout can be thought of as looking like damping and additional force gradient to a pilot and affect the numerical description of the pilot's behaviour in a tracking task in a similar way. These results reinforce the notion that there is a range of feel system characteristics to which pilots can adapt readily. Outside this range, the parameters of the neuro-muscular system and in fact the central nervous system begin to change, dramatically in some cases.

Effects of feel system on central nervous system model

According to the model being considered, (Figure 4-35), the operation of the pilot model as a whole is determined by characteristics of the central nervous system and the limb-manipulator closed loop system, i.e.:

$$Y_p = Y_{cns} Y_{lm} \tag{4.32}$$

The input of the central nervous system model Y_{cns} is the tracking error, the output of the model is the intended limb position, which is the input of the neuromuscular model Y_{ns}. Therefore, it would seem natural to assume that all changes in the central nervous system model are determined only by the controlled element (the airplane). This means that the effects of feel system characteristics on the model Y_{cns} parameters can appear only if they cause any changes in the aircraft behaviour.

Analysis shows that at low frequencies, the model for Y_{cns} can be described by the familiar:

$$Y_{cns} = K_{cns} \frac{(T_L s + 1)}{(T_I + 1)} e^{-\tau_{cns} s}. \tag{4.33}$$

This is precisely the form used to describe pilot action in compensatory tracking by many authors, e.g. Efremov Efremov, Ogloblin, Predtechensky, and Rodchenko, (1992), McRuer and Krendel, (1974). The identified frequency responses in the current work of Ycns and Yp however show that frequency responses of Y_{cns} have *two* visible peaks: the first at 6.5 rad/sec, the second at 18 rad/sec. The presence of two peaks is due to the fact that the central nervous system both controls operation of the neuromuscular system and performs tracking. This is why equation (4.33) is not suitable to describe the entire frequency range.

According to the data received, the following transfer function form is postulated:

$$Y_{cns}(s) = K_{cns} e^{-\tau_{cns} s} \frac{(T_L s+1)}{(T_l s+1)} \frac{1}{(T_1^{\ 2} s^2 + 2\zeta_1 T_1 s+1)} \frac{1}{(T_2^{\ 2} s^2 + 2\zeta_2 T_2 s+1)} \qquad (4.34)$$

where

K_{cns} is the gain constant

τ_{cns} is pure time delay

T_L and T_l are lead and lag time constants created by pilot while flying

T_1, T_2, ζ_1, and ζ_2 are time constants and damping ratios of the second-order filters which determine the model Y_{cns} response to the changes in the controlled element caused by the changes in the feel system characteristics.

Figure 4-43 shows describing functions and transfer functions in Bode plot form for the pilot model and for the central nervous system model for four configurations of the feel system. This figure shows the response to feel gradient. These were the same pilot, flying each configuration 3 times. The gradients are: upper left, = zero; lower left = 203 N/M; upper right = 400 N/M; lower right = 800 N/M. The symbols represent the extracted describing function; the lines represent the derived transfer functions considering all the data.

The frequency responses in Figure 4-43 show that the low-frequency portion (up to 3-4 rad/sec) of the model Y_{cns} do not practically change with feel system characteristics. This is due to the fact that the low-frequency part of the model determines the control of the visual input, and characteristics of this control are determined by characteristics of the controlled element. In these experiments, the aircraft dynamics (τ_r=0.7) were constant, so for airplanes with a roll mode time constant of 0.7 sec, the low frequency parameters of Y_{cns} can be considered to be constant.

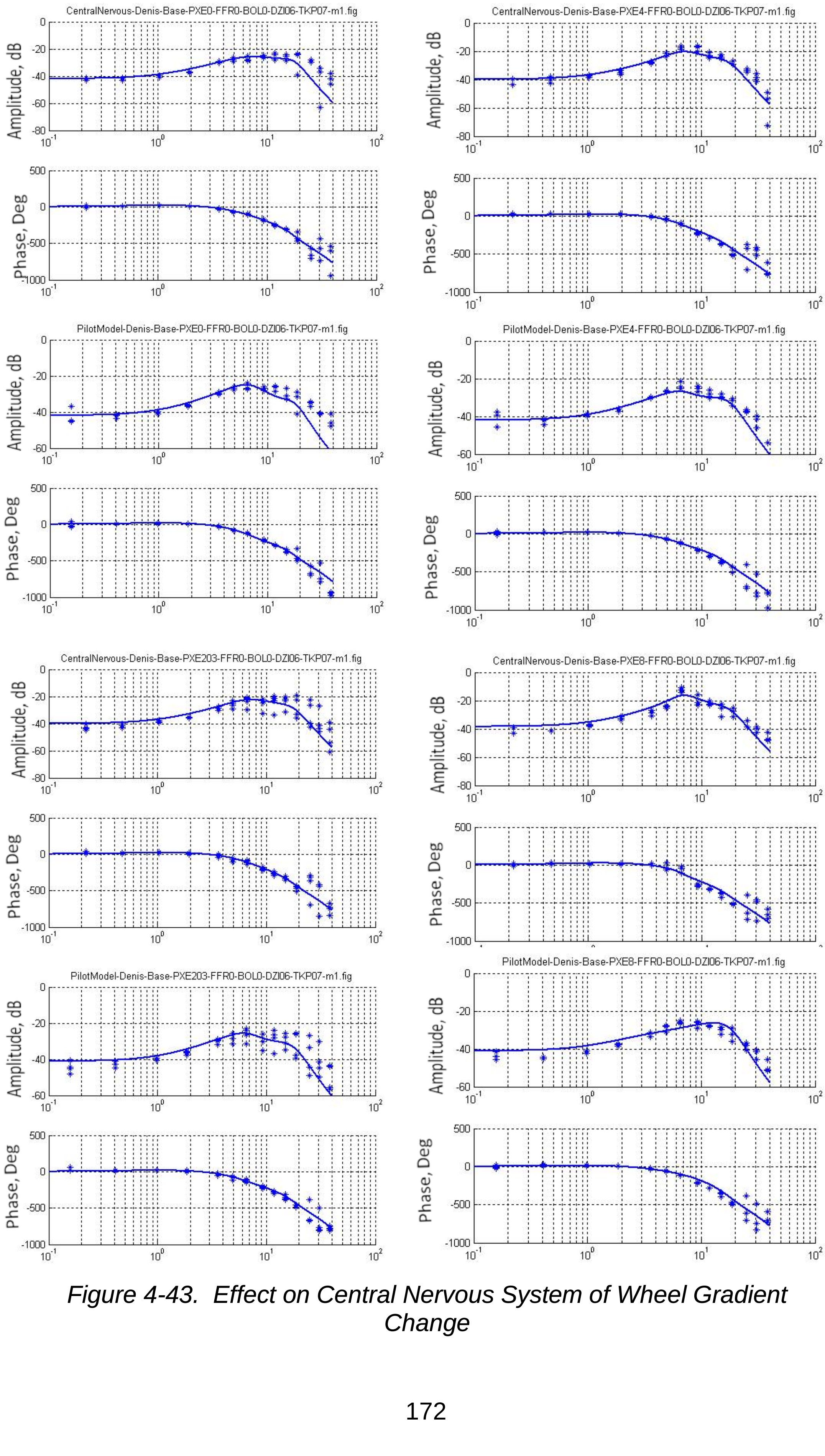

Figure 4-43. Effect on Central Nervous System of Wheel Gradient Change

For the high frequency filters, nearly all of the terms are also constant. Nevertheless, as the force gradient increases, the first peak (with damping ratio ζ_1) increases slightly. The increase is shown as a decrease in damping ratio ζ_1 in Figure 4-44.

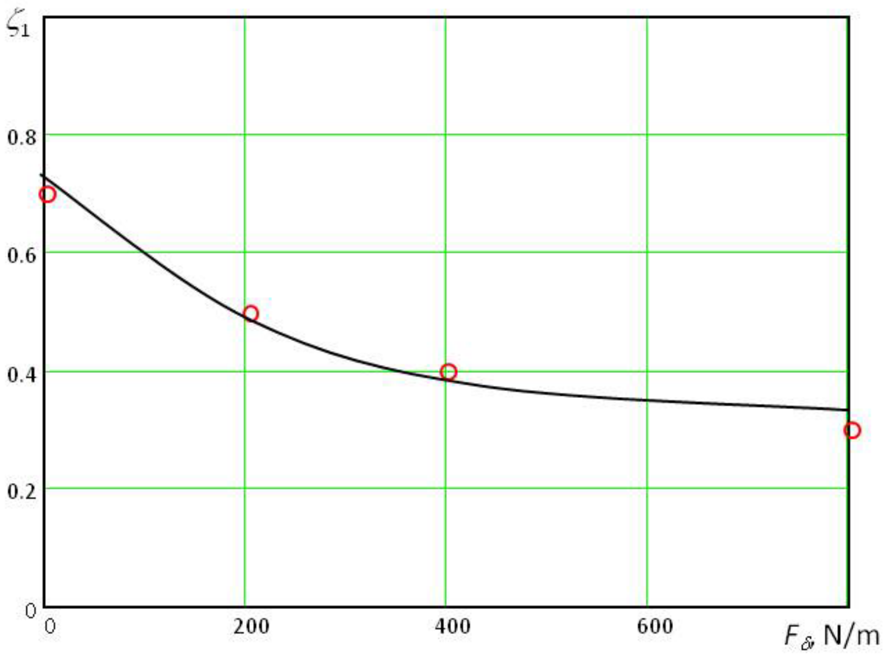

Figure 4-44. Effect of Spring Gradient on Damping Term (ζ_1) in CNS Transfer Function

4.3.6 Summary of Human Pilot Dynamics Investigations

Piloted simulations were conducted using a multi-loop tracking task in order to extract the effects of feel system changes on mathematical models of the human pilot. The planning of these tests considered the unique data requirements of the analysis technique to perform the describing function extraction in both loops simultaneously.

Data analysis demonstrated that the process works: models of the neuro-muscular system, the limb-manipulator system ,the central nervous system, and the pilot as a whole were extracted. The describing functions were then fitted with transfer functions and the coefficients determined for a best fit of the extracted data. While there is some scatter as would be expected, the transfer functions fit the data quite well.

Further analysis of the data reveals the "inner workings" of the pilot in response to changes in the feel system. The only way this data would fit a transfer function model was to include a second-order term in the numerator of the neuro-muscular model. This has not been done before. This model feature is responsible for the "Dip" in the identified frequency response which changes dramatically as a function of feel gradient.

Nonlinear elements were evaluated as well. For small deviations around "normal" values, the effects on the elements of the pilot model of breakout force were similar to those seen with changes in spring gradient. For similar regions around "normal", changes in friction produced pilot model changes similar to changes in damping.

4.3.7 Thoughts on the Meaning of Pilot Models and Use of the Results

Human pilots as controllers are amazing in their ability to adapt. The capability for adaptation ranges from changing the strategic organization (or choice) of loop closure technique to the ability to generate lead, lag and dramatic gain variations within a single strategy. Moreover these changes can be made consciously, or unconsciously, and very rapidly "on the fly" (pun intended). This author's experience is that pilots are far from being mathematically stationary controllers. If a tracking task gets too long (on the order of a couple of minutes), pilots will be seen to "experiment" with different techniques. Whether out of boredom and the desire to try something different, or borne of frustration or dissatisfaction with performance at any given moment, pilots will change their techniques. These temporal variations are very difficult to identify with frequency-based, time-averaged analysis techniques. It can be easy for a small PIO in the middle of a 2-minute tracking task to go unnoticed because the analysis technique averages it out. For this reason, real-time monitoring is important, whether via automated methods (e.g. Mitchell and Klyde (2004, 2005, 2008)), or by having an experienced handling qualities engineer on the flight deck. This is also why wavelet-based techniques (e.g. Thompson, et al (2001), Bachelder and Klyde 2003), and Thompson, et al (2004)) show so much promise for the future.

What can be said is that “on average”, pilots are *capable* of performing as measured here. While there is sometimes wide variation in the measured responses, the general character of the pilot’s response remains similar across the pilots.

One implication of this is the notion that measured pilot models, derived from tracking experiments as reported here should not be considered as representative of average pilot flying behaviour. Rather, they should be taken as representative of average *limiting behaviour*. This understanding of the limits of closed-loop capabilities is useful from a stability point of view, in cases in which pilots might try to achieve best performance. Because pilots don’t typically, day-in-day-out attempt best precision performance, these results do not represent “average” piloting behaviour. On occasion, however, pilots might *try* to achieve best precision performance, and it’s important to understand just where that boundary is vis-á-vis closed loop stability.

4.4 Assessing PIO Propensity

The various metrics for predicting and classifying PIO considered by Mitchell and Hoh (2000) can be broadly classified as “slope-based” metrics, “absolute” metrics, and “pilot model-based” metrics.

While Bandwidth/Phase delay is perhaps the most extensively vetted, and so far probably the most reliable predictor, it shares a trait with Gibson in that it only evaluates the airplane dynamics at and beyond the frequency at which the phase goes beyond 180 degrees (ω_{180}). To this, Gibson adds a consideration of the frequency at -180 and the gain: if the open-loop gain is too large, the pilot can still push the airplane into instability.

Each of these researchers, Neal and Smith, Hoh, Gibson, were obviously on to something significant: Neal and Smith recognized the significance of the resonant peaks in piloted closed loop response, Hoh recognized the significance of phase roll-off, Gibson added the significance of gain. These notions will now be extended and unified in Dynamic Oversteer.

4.4.1 Dynamic Oversteer Criterion

Note: The Dynamic Oversteer Criterion and the technology related to it is patent protected.[*]

Returning to the notion introduced in Chapter 1, in reality, pilots use a variety of techniques when they fly airplanes. They sometimes fly the airplane in an open-loop manner, allowing it's natural (or augmented) stability to reject disturbances, and only "enter the loop" occasionally, perhaps to adjust the flight path slightly as necessary. At other times, they fly actively "in the loop", continuously making control inputs to actively drive the airplane flight path (sometimes more precisely than others[†], but nevertheless, actively regulating or commanding flight path in a more-or-less continuous manner). Pilots' switching between modes was explained by Rasmussen and described in Chapter 1. Unfortunately, true opportunities for a pilot to engage in genuine closed loop control in large airplanes are few and far between. Operationally, for military transports, in-flight refuelling is a good example. For commercial transports, the most intense opportunity is probably the landing flare. The difficult bit about this is that, done properly, the flare consists of only a few seconds of intense, closed loop precision path piloting. This is difficult for a number of reasons. For pilots, it means they only get to "practice" true closed loop control for a few seconds at the end of usually long flights. For engineers, the data available usually only lasts a few seconds.

[*] See Hiltner and Lee (2007)

[†] Consider, for example the difference between flying through a turbulence field at altitude and controlling the flare to effect a precise touchdown. In regulating against disturbances at altitude, the pilot is probably less likely to be trying control altitude to +/- 10 feet than he is to simply keep the flight path close to desired. In the case of the flare, that +/- 10 feet tolerance is obviously too large, and the pilot will be "tightening his control loop" by increasing his gain to reduce the tolerances.

For these reasons, it's not uncommon for engineers to define special tasks in order to prolong the manoeuvre and allow its study. Some examples of special manoeuvres used in this way can be found in Lee (1997, 2000a, 2000b, 2001). These are used in an attempt to generate true closed-loop pilot-airplane interaction data which lasts for more than a few seconds in order to facilitate analysis of the interactions between the pilot and the airplane.

In general, it can be said that pilots expect and appreciate linear response characteristics. That is if they make a control input and observe the response, they will expect that twice that input would generate twice the response. This is representative of a linear open-loop response, depicted in Figure 4-45.

Consider the structure of Figure 4-45 with the roll axis of a transport airplane of the form

$$\frac{p(s)}{\delta(s)} = \frac{K_c}{s(s + 1/\tau_r)} e^{-\tau s} \tag{4.35}$$

It is illustrative to look at the response to pilot inputs which might vary both in frequency and in amplitude (pilot gain). To illustrate that response, consider pilot inputs of the form:

$$\delta_{Pilot}(t) = K_p \sin(\omega t) \tag{4.36}$$

The result, presented in terms of open loop response amplitude vs. frequency of the open-loop input is as seen in Figure 4-46. Here, the airplane response is quite regular with variations in pilot input. Variations in pilot gain (that is, size of the input) produce predictable variations in the output across the frequency range. Variations in pilot input frequency similarly produce regular, predictable variations in airplane response at each gain level. Moreover, the response diminishes with increasing frequency. Pilots have learned through experience these regularities of motion and are quite adept at making use of these regular, predictable responses to make the airplane go where they want it to go (analogous to Rasmussen's skill-based repertoire of behaviours which are put into play at just the right time, echoed in McRuer's SOP as the pre-cognitive strategy, and suggested by Field (1995) as the strategy pilots *must* use for large transport aircraft).

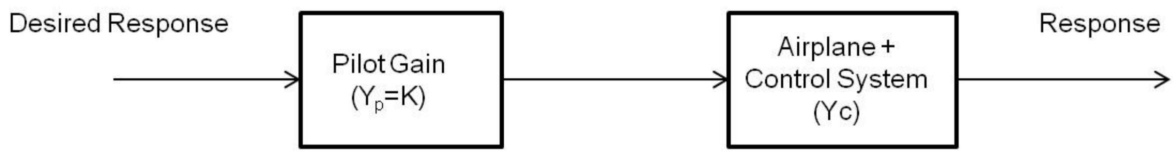

Figure 4-45. Open Loop Structure

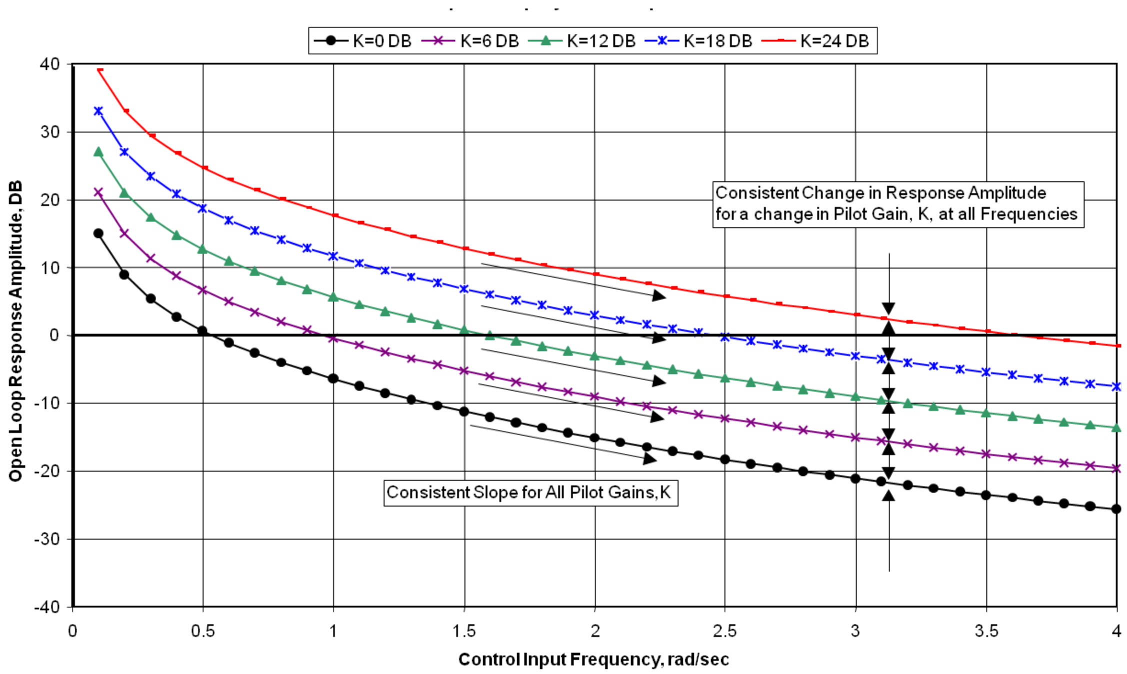

Figure 4-46. Open Loop Response Regularity

When the pilot actively closes a loop, as in Figure 4-47, however, the character of those responses looks very different, as depicted in Figure 4-48. Here, for each value of pilot gain, the airplane response across the frequency range of interest shows a resonant peak followed by attenuation. Moreover, at each increased value of pilot gain, the resonant peak appears at a different frequency, and with a different amplitude. This is not news to a controls engineer: it is simply a consequence of the pilot+airplane curve cutting across the closed-loop gain curves on the Nichols chart. In fact, this resonant peak is precisely what was noticed by McRuer and Gibson(1999) as the “PIO syndrome”. It is not a PIO in and of itself, but a normally expected consequence of actively closing the loop.

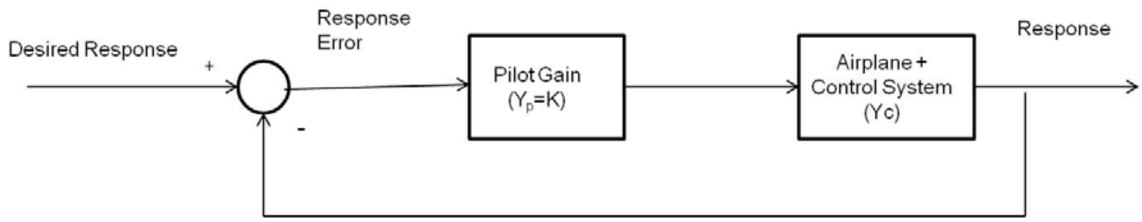

Figure 4-47. Closed Loop Structure

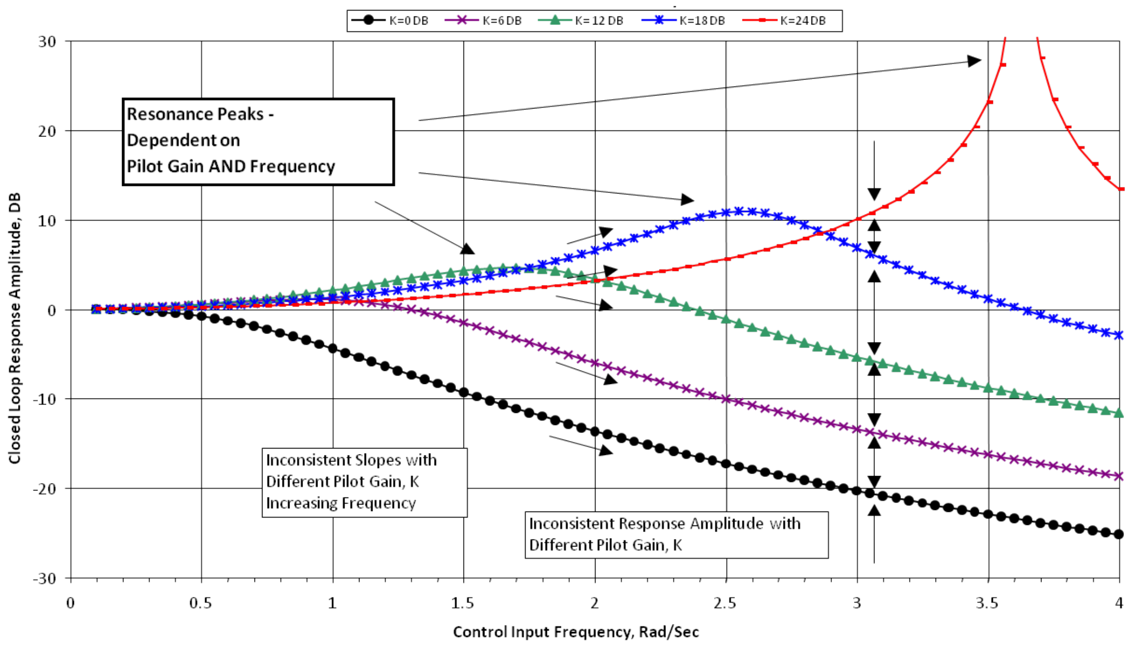

Figure 4-48. Closed Loop Responses are not Predictable

It might be news, though, to a pilot who spends most of his flying career making measured, pre-programmed, open loop inputs, expecting to get the same response he’s gotten before. If the pilot were to suddenly change from the open-loop pre-cognitive strategy to attempting to close the control loop, he may well be surprised to find this resonance. Further, in an attempt to correct for what might be an initial overcontrolling “bobble”, the pilot may well increase his gain. In so doing, the pilot may well begin “chasing” the highest performance input, that is, adapting to what he observes as the resonant peak in output response, particularly if urgency is high. This behaviour has in fact been observed in power spectral density analysis of pilot inputs. It is not uncommon to see powers at very low frequency in open-loop control situations shifting to higher and higher frequencies as the urgency (and consequently the pilot's gain) increases.

What is significant, though, is the *recognition* that if one were to construct a locus of those resonant peaks, it would run asymptotically to the PIO frequency. This is illustrated in Figure 4-49. This is the first major step to understanding the Dynamic Oversteer phenomenon.

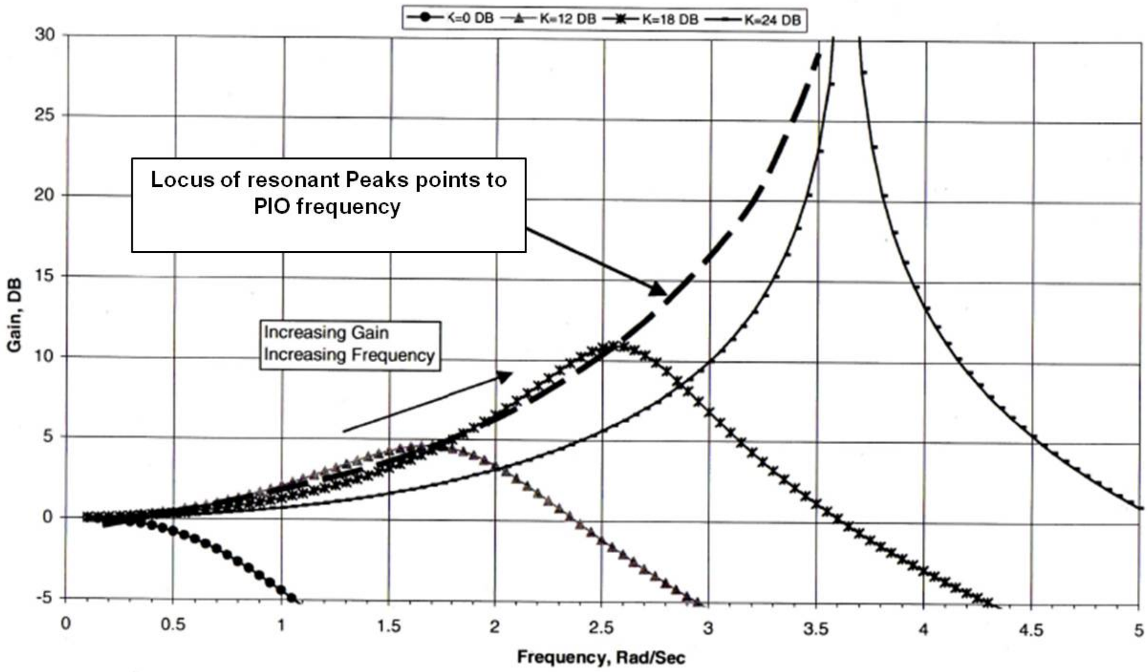

Figure 4-49. Locus of Resonant Peaks

Concept and Definition

The oversteer criterion focuses on the magnitude of the resonant peak *relative to the magnitude of the pilot input*. When the magnitude of the resonant peak increases faster than the pilot gain, dynamic oversteer occurs. This gives rise to the definition:

Dynamic Oversteer is defined as the system condition at which the closed loop resonant response peak increases faster than the pilot (open loop) gain increases (db to db). An additional necessary condition is that the closed loop response gain (output/input) be greater than 1 (the system must be amplifying the pilot input).

Nichols Charts

The closed-loop resonant peak can be seen on a Nichols Chart, defined by the point of tangency between the open loop frequency response and the lines of constant closed-loop amplitude. An example is shown in Figure 4-50.

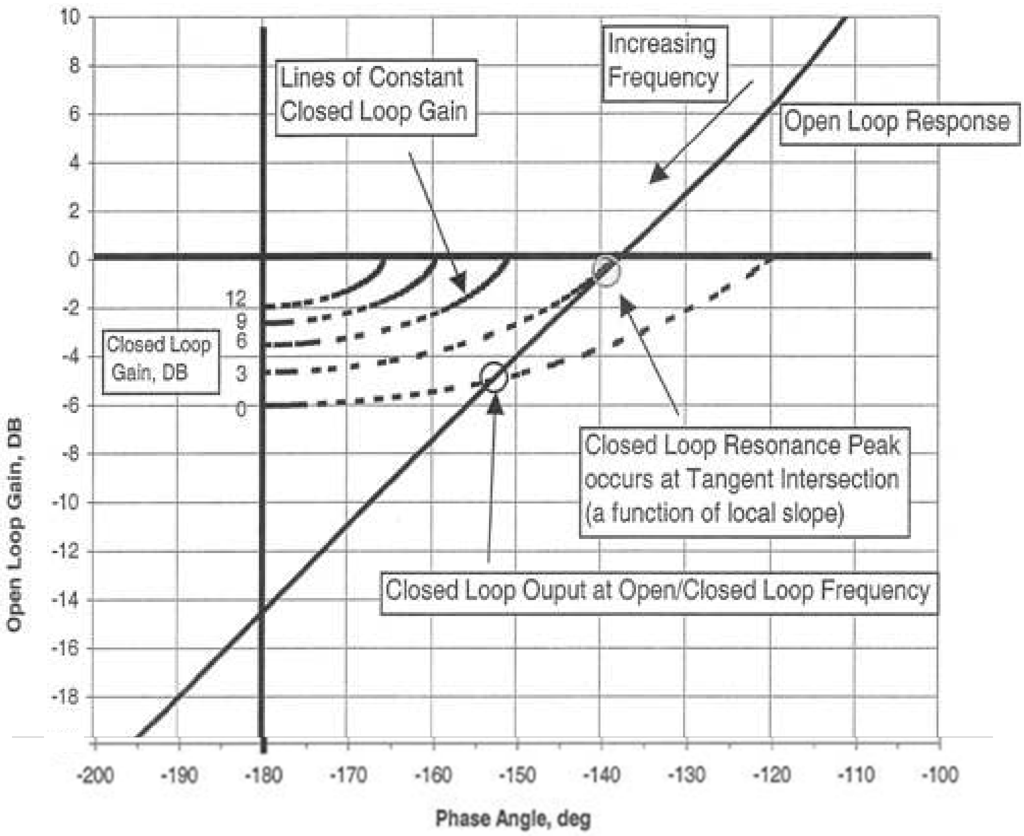

Figure 4-50. Nichols Chart Frequency Response

The effect of pilot gain increase can be seen by simply moving the open loop frequency response curve vertically by an amount corresponding to the additional pilot gain. In doing this, care should be taken to check whether deflection or other limits are exceeded in the analysis. For example, if the open-loop frequency response characteristics are defined for full-deflections of the controls, additional pilot gain is not available without exceeding the practical limits of the system. For this analysis, linear characteristics have been assumed. This may not be completely accurate for real airplanes with real systems, but it is acceptable for the purpose at hand. An example of analysis including varying the pilot gain is shown in Figure 4-51.

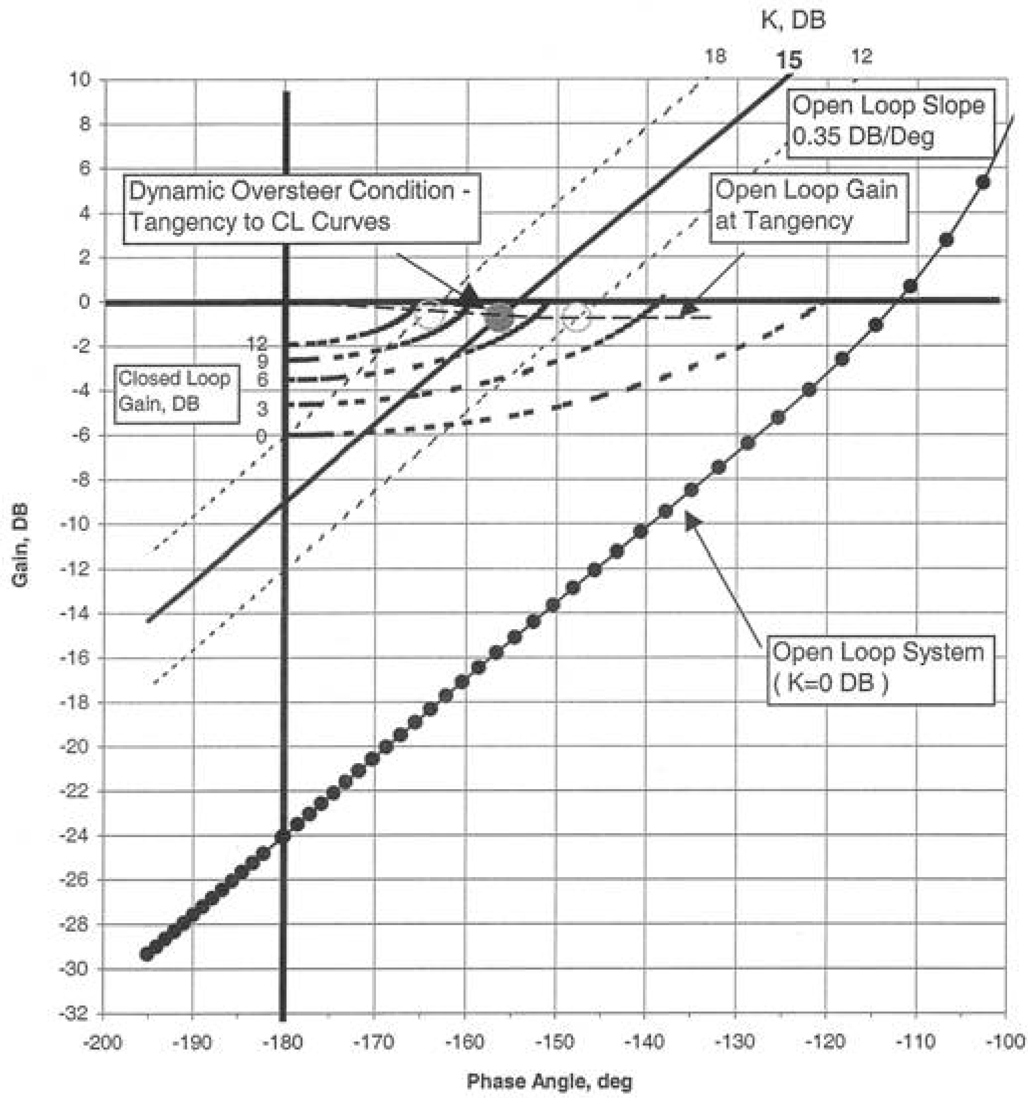

Figure 4-51. Variation of Resonant Peak with Pilot Gain, K.

Plotting the peak resonant amplitude variation with pilot gain variation, as in Figure 4-52, illustrates the relationship: the response gain / pilot gain is not constant with pilot gain. At some point, the response resonant peak grows faster than the pilot gain increase. When this ratio becomes greater than 1.0, the system is considered to be in an oversteer condition. This is illustrated in the figure for the example case presented.

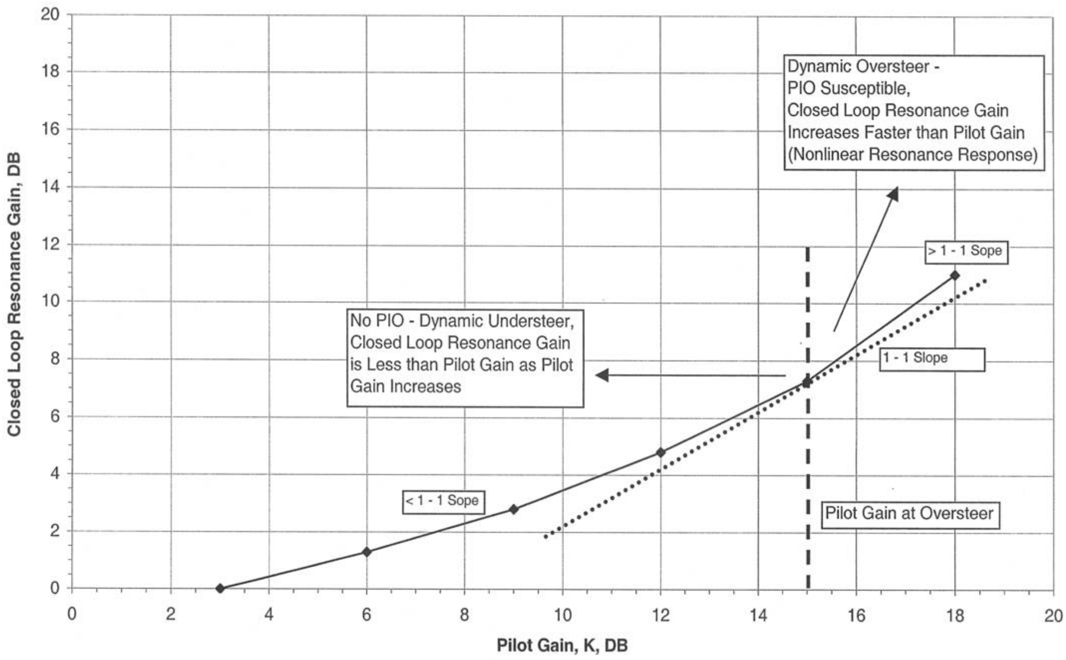

Figure 4-52. Defining the Oversteer Condition

The local slope of the frequency response curve, and how it intersects the closed-loop gain curves on the Nichols chart is the determining factor in determining the oversteer condition. For each local slope, the oversteer condition occurs at a different phase angle and a different open-loop gain. Figure 4-53 shows the oversteer condition for two different open loop frequency response slopes.

This suggests that the local slope might be used as a reference to define the phase angle and gain at oversteer. The phase angle at the oversteer condition is shown in Figure 4-54. As is seen this curve has units of gain / phase angle which is a function of phase angle. This can be integrated by phase angle to get a gain as a function of phase angle which is at the oversteer condition. What is of interest is the slope of this integrated curve as a function of phase angle, not the absolute value of the gain.

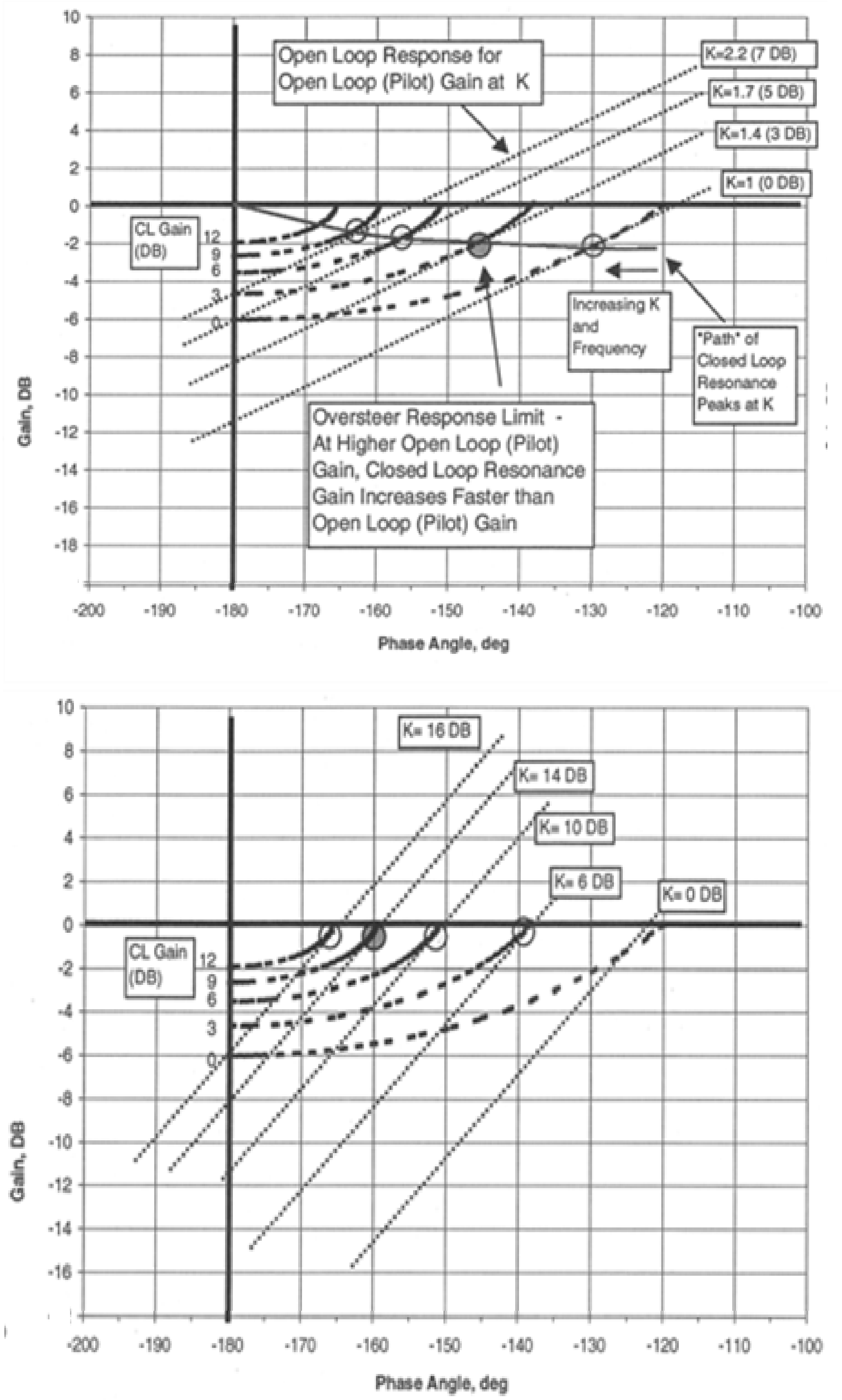

Figure 4-53 Identifying the Oversteer Condition at Different Open Loop Slopes

The integrated curve can now be plotted directly on a Nichols plot. The point at which the open-loop frequency response curve is tangent to this integrated curve (the point at which the slopes match) defines the phase angle at oversteer. The open-loop gain at oversteer can also be plotted directly on the same Nichols chart as a function of phase angle. The pilot-supplied gain which will result in oversteer is then the difference between this open-loop gain and the frequency response gain at the point of tangency to the integrated phase angle curve. This process is illustrated in Figure 4-55. Here, the oversteer limit and gain curves have been determined numerically via a proprietary process of iteration in the complex plane.

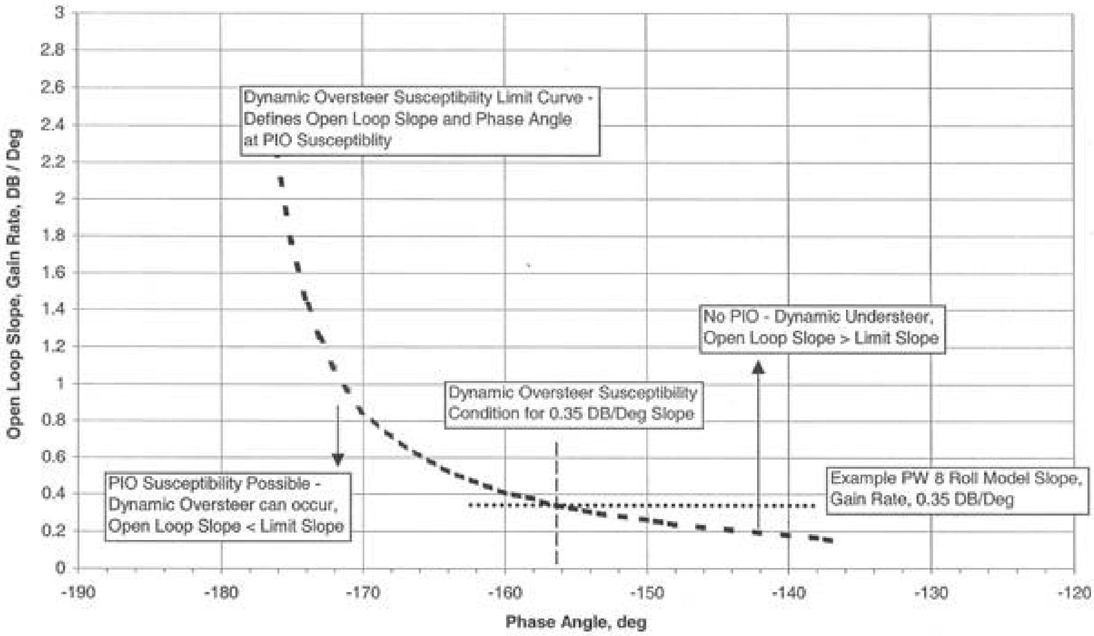

Figure 4-54 Oversteer Susceptibility Limit Curve

Low slope oversteer condition

The local slope susceptibility curve of Figure 4-54 was integrated numerically to provide a tangency point (point of matching slopes) which would define the oversteer condition as a function of phase angle. As seen from Figure 4-55, the range of phase angles is limited to approximately -135 degrees, at which point the slope limit is approximately 0.15 db/deg. The open loop gain associated with these phase angles defining the over steer condition is near the 0 db open loop line. These slopes and phase angles also all have a closed-loop resonance gain greater than 1.0.

During development of the numerical solution for the susceptibility and limit gain curves, it was noticed that a solution was also possible for lower slopes and phase angles. These solutions are shown in Figure 4-56 and 4-57

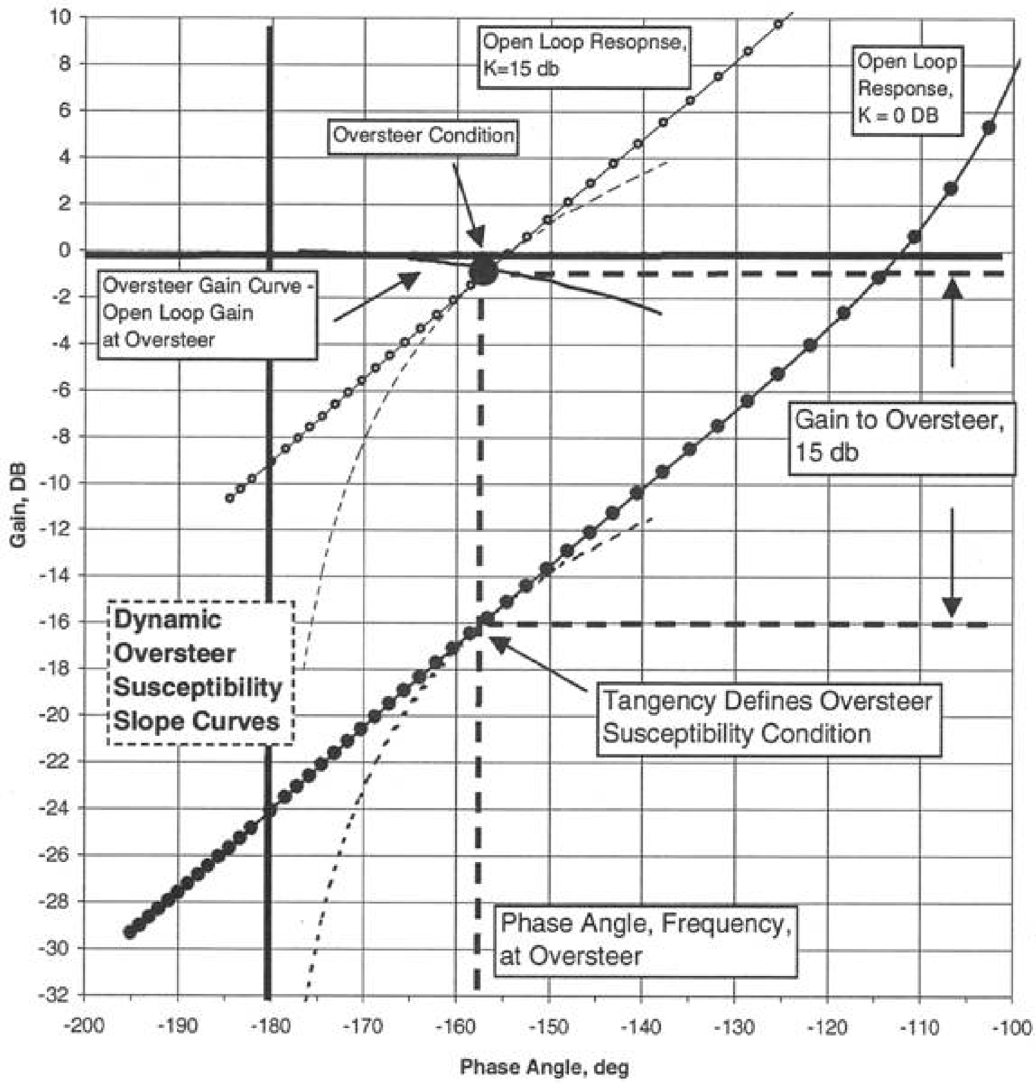

Figure 4-55. Use of the Nichols Chart to define the Oversteer Condition

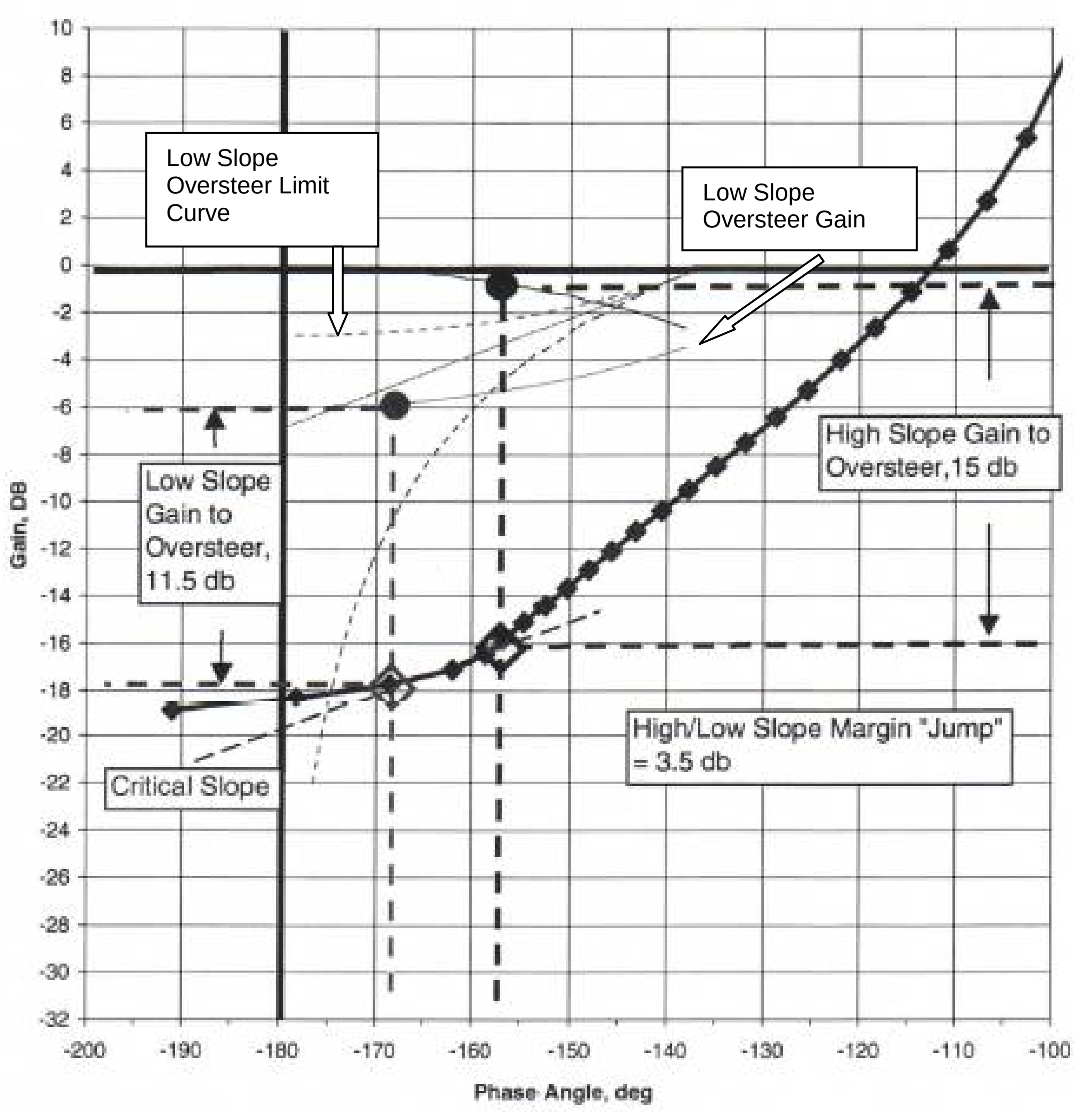

Figure 4-56 Low Slope Limit Curves and Critical Slope Crossing Example

This low-slope solution has some characteristics which are significantly different from the higher-slope conditions. Both susceptibility slope curves converge to the same slope near -135 degrees phase angle. The low slope susceptibility curve, however, becomes increasingly shallow until reaching zero slope at -180 degrees phase. The range of slopes is relatively small, but the significance can be seen in the oversteer limit gain curve. The fact that the low-slope limit gain curve is in fact the 0 db closed-loop resonance curve identifies any frequency response with that low slope as being continuously in oversteer. The impact of this is that the pilot gain required to reach oversteer can be as much as 6 db *lower* than that for the high-slope case.

This suggests that a shift from the high-slope to low-slope curves could potentially generate a step reduction in open loop gain at oversteer. An extreme example is postulated in Figure 4-56. In this illustration, the frequency response reaches the oversteer tangency condition at approximately -157 degrees phase. The gain to oversteer at that point is 15 db. If then some system characteristics cause a further increase in phase with very little gain, as depicted, the system would reach a low-slope tangency condition at a phase angle of -168 degrees. At this point, the gain to oversteer is 11.5 db, which is 3.5 db lower than the high-slope case. The system could be operated without PIO susceptibility with a pilot gain of 13 db below -158 degrees phase, but any increase in phase as a result of an increase of input frequency would result in PIO susceptibility. This might be considered a "jump" in the susceptibility due to the transition from high to low slope condition.

Another condition in which the critical slope might be violated was given by Gibson (2000) for the actuator saturation example, shown in Figure 4-7 which shows the very dramatic slope change when the actuator saturates.

Because of the fact that any frequency response slope less than the critical transition slope results in continuous oversteer, the high-low slope transition is considered to be a condition to be avoided.

All of the slope- and margin defining curves are presented in Figure 4-58 as a graphical template in a Nichols plot presentation. This allows plotting an airplane's open loop frequency response curve and reading off the values directly.

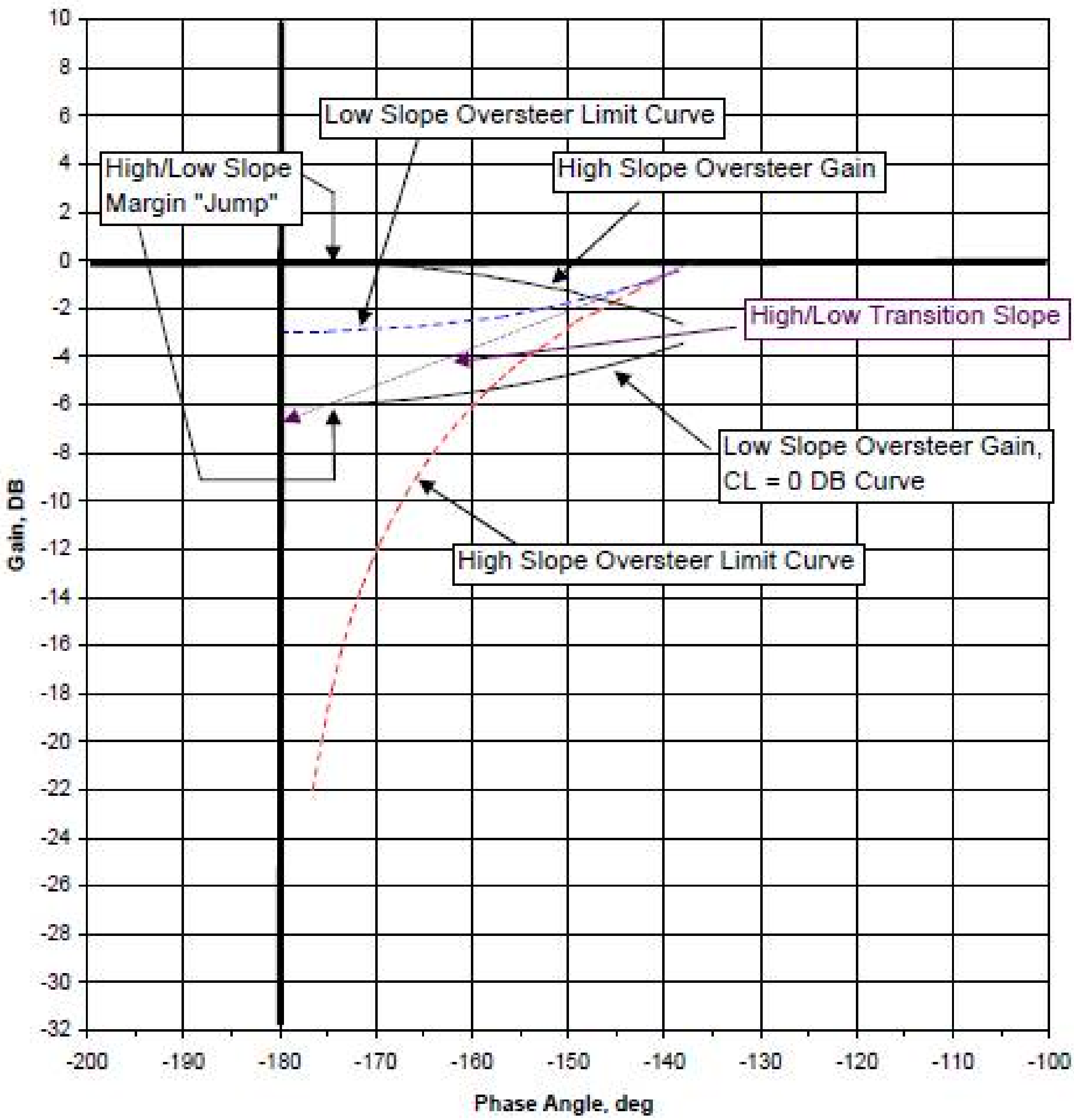

Figure 4-57. Template Definitions

Definition of Margins

The oversteer condition identifies the potential for achieving a PIO: the airplane dynamic response is "running away" from the pilot, if the pilot elects to stay in the loop and chase it. To be in a PIO, the pilot gain and frequency have to be sufficient to achieve an open loop gain greater than 1.0 at -180 degrees of phase. In addition, the frequency response must not exhibit a slope less than the critical slope in order to avoid the potential for a "jump" in oversteer gain.

Using this knowledge, three margins have been identified, illustrated in figure 4-58, along with an example with data derived from Gibson (1999).

- Oversteer margin is the gain between the oversteeer tangency point and the oversteer limit gain curve. This is the pilot gain required to reach oversteer, the condition at which the resonant peaks grow faster than the pilot inputs. It is a direct measure of system sensitivity to oversteer.
- Oversteer to PIO margin (OS-PIO) is the gain between the oversteer tangency point and the gain at -180 degrees phase. This is the gain required of a pilot to reach instability once in oversteer. Large margins give the pilot more opportunity to recognize the situation and change his strategy (e.g. reduce gain) prior to reaching instability.
- PIO margin is the gain between the -180 degree phase crossing of the critical slope extended from the tangency condition and the -180 degree phase crossing of the frequency response curve. This margin indicates, first, if the critical slope has been crossed (potential jump phenomena in the gain-to-oversteer margin). It also provides consideration for the phase at which the tangency condition takes place. Oversteer tangency at lower phase angles and correspondingly lower frequency is considered more susceptible to PIO than at higher phase angles. Therefore, more OS-PIO margin would be required for early phase tangency conditions, and this is accommodated by using the critical slope as a reference for PIO margin.

Numerical values of these margin parameters have been used to discriminate between configurations with good characteristics and those with not-so-good characteristics. Those data are not presented here.

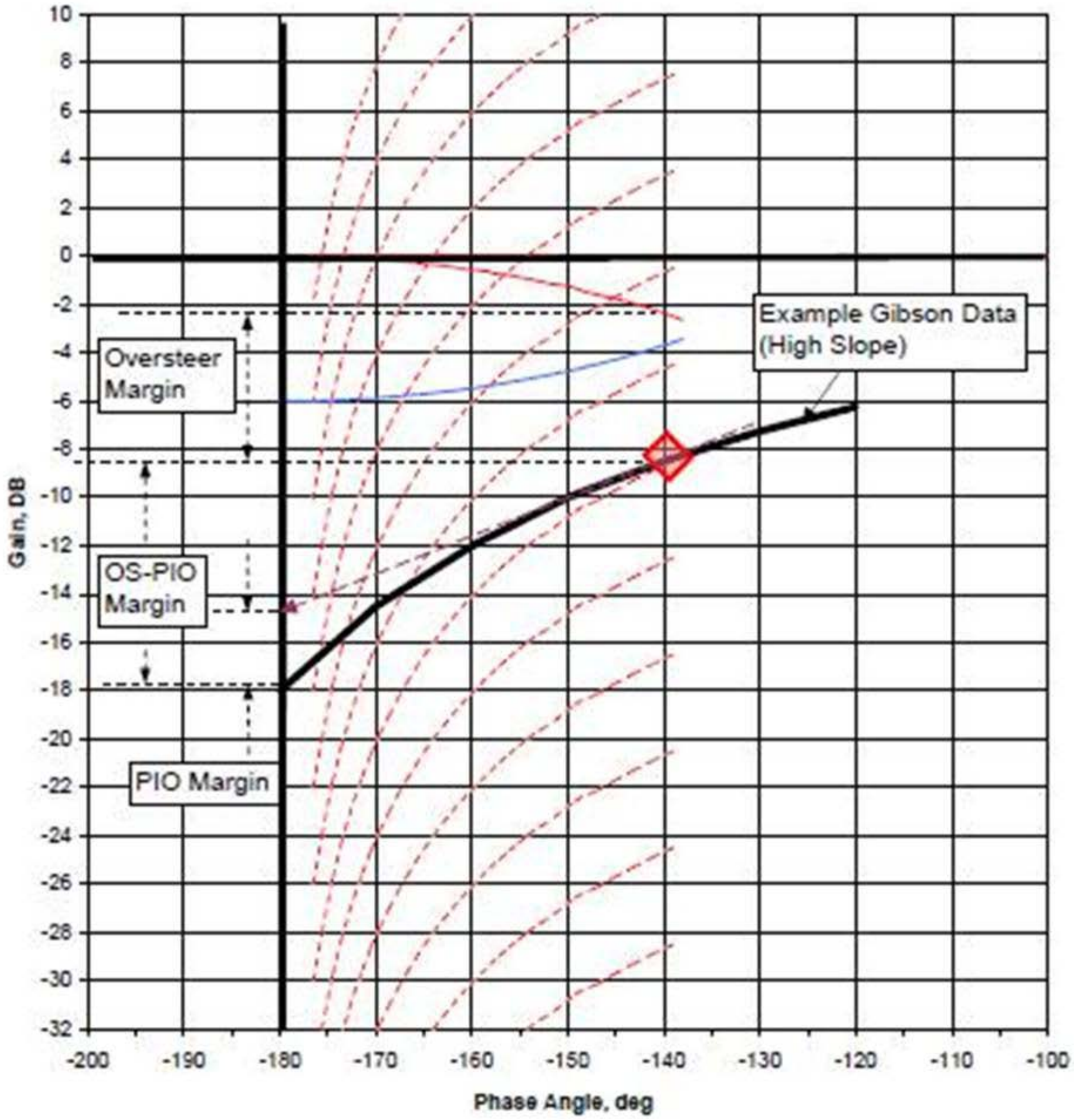

Figure 4-58. Margin Definitions

4.4.2 PIO Propensity Summary

Extending the work of Hoh and Gibson in terms of recognizing the root causes of pilot induced oscillation, the Dynamic Oversteer criterion introduces a unique addition to the body of knowledge. While Hoh recognized the importance of the phase delay, and Gibson introduced the notion of pilot gain and sensitivity, each of those focused only on the characteristics at and beyond the -180 degree phase point. The new knowledge introduced by Dynamic Oversteer is that there are characteristics prior to ω_{180} which will lead the pilot to the PIO. Dynamic Oversteer recognizes this point (the Dynamic Oversteer point) as a point of change in the predictability of the response. From that point, any increase in pilot gain, or increase in frequency in an attempt to improve performance will drive the pilot to the PIO. The criterion has been developed and documented and validated against a number of platforms.

4.5 Summary

Large aircraft have been shown to exhibit slow modal frequencies. Moreover, the short period and phugoid modes tend to get closer together as airplane size increases. As stability is relaxed, short period natural frequencies get even slower, but perhaps more importantly, the character of the motion, as defined by the eigenvectors changes considerably. There is some evidence that pilots simply adapt by adopting new techniques, and this new technique is seen in time history analysis, it also suggests that pilots need an “internal model” to help them predict the effects of a given control input.

With slow natural frequencies comes long times (in seconds) for any transients to die away. The consequence of this has been shown to be in the amplitude of the response. Essentially, pilots are seen as always being in the transient response, so whenever an input is made, it is made with a non-zero initial condition. This is not the case typically analyzed by designers.

It has been shown that the length of time for unsteady lift development to take place is a direct function of the size of the lifting surface chord. As airplanes get dimensionally larger, the lag associated with the unsteady lift may no longer be negligible for handling qualities analysis.

Simple first-order hydraulic actuator models typically used have been shown to be not conservative in terms of the phase contribution they bring to the whole motion of the airplane, and the contribution can be significant. More accurate second and third order actuator models have been suggested, and the difference in lag has been quantified.

Cockpit feel system characteristics were examined extensively. Experiments were conducted to evaluate minimum resolution in the pilot's ability to manipulate a transport aircraft wheel controller. In general, pilots could generate increments of 0.5 degrees with force increments of 0.5 lbs. A theoretical method was developed to estimate optimum combinations of feel system parameters. Comparison with the measured boundaries produced a good correlation. Experiments were also conducted to determine handling qualities directly as a function of feel system parameters for landing tasks with a wheel controller in a large transport.

Two extensions to Hess's Linearity Index were attempted to remove the limitation that friction be equal to breakout in his original version. These extensions were evaluated against results of the handling qualities evaluations conducted in the simulation experiments with the conclusion that while these extensions could identify negative effects of excessive breakout, neither correlated well with measured results: iso-linearity lines did not correlate well with iso-handling qualities lines.

Piloted simulations were conducted using a multi-loop tracking task in order to extract the effects of feel system changes on mathematical models of the human pilot. The planning of these tests considered the unique data requirements of the analysis technique to perform the describing function extraction in both loops simultaneously.

Data analysis demonstrated that the process works: models of the neuro-muscular system, the limb-manipulator system ,the central nervous system, and the pilot as a whole were extracted. The describing functions were then fitted with transfer functions and the coefficients determined for a best fit of the extracted data.   While there is some scatter as would be expected, the transfer functions fit the data quite well.

Further analysis of the data reveals the “inner workings” of the pilot in response to changes in the feel system. The only way this data would fit a transfer function model was to include a second-order term in the numerator of the neuro-muscular model. This has not been done before. This model feature is responsible for the “Dip” in the identified frequency response which changes dramatically as a function of feel gradient.

Nonlinear elements were evaluated as well. For small deviations around “normal” values, the effects on the elements of the pilot model of breakout force were similar to those seen with changes in spring gradient. For similar regions around “normal”, changes in friction produced pilot model changes similar to changes in damping.

Extending the work of Hoh and Gibson in terms of recognizing the root causes of pilot induced oscillation, the Dynamic Oversteer criterion introduces a unique addition to the body of knowledge. While Hoh recognized the importance of the phase delay, and Gibson introduced the notion of pilot gain and sensitivity, each of those focused only on the characteristics at and beyond the -180 degree phase point. The new knowledge introduced by Dynamic Oversteer is that there are characteristics prior to ω_{180} which will lead the pilot to the PIO. Dynamic Oversteer recognizes this point (the Dynamic Oversteer point) as a point of change in the predictability of the response. From that point, any increase in pilot gain, or increase in frequency in an attempt to improve performance will drive the pilot to the PIO. The criterion has been developed and documented and validated against a number of platforms.

Figure 4-59 787 Single Engine Go-Around Demonstration

Right engine failed. Note rudder deflection. Outboard ailerons are not visible, but note flaperon (slotted surfaces between flaps) positions; spoilers are not deflected. Also note tailplane deflection at this low-speed condition. Photo courtesy of Allen Ball.

5 Summary Discussion

Knowledge comes, but wisdom lingers.

Alfred, Lord Tennyson*

It is astonishing what force, purity, and wisdom it requires
for a human being to keep clear of falsehoods.

Margaret Fuller†

The title of this work was carefully chosen to direct (or to bound?) this course of discovery. In this course the goal was to explore the characteristics of large transport aircraft and how models of the control system and pilot (and the airplane as well) could inform handling qualities analysis. The ultimate challenge for a handling qualities engineer is the Pilot Induced Oscillation.

Handling qualities is all about tailoring the dynamics of the airplane to those of the pilot in an attempt to produce a safe, efficient enterprise for manoeuvring. Chapter 2 explained that it took decades for the industry to come to an understanding that it really is about what the pilot wants (or rather, needs). That job continues to be a challenge for at least two additional reasons.

A master, mentor, and dear friend named Bob Wattson once explained:

> "*Pilot opinion* is valid and quantifiable*; pilot's opinions* are subject to bias and should not be trusted."‡

A second reason that this task is so difficult is the very real fact that

> "good pilots can learn to fly deficient airplanes well".

There are times when the pilots honestly do not know what they want and honestly cannot see any difficulty. Yet, airplanes must be designed to be flown by a population larger than company test pilots.

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* Alfred, Lord Tennyson was Poet Laureate of the United Kingdom with the longest term (Tennyson, 1744)

† Sarah Margaret Fuller Ossoli was an influential journalist in the US in the early part of the 19th century. (Ossoli, 1852)

‡ …at least that's the paraphrase for posterity. The original words were somewhat more colorful. Personal communication c. 1981,.

The principle results have shown that:

The dynamic response of large transport aircraft is dominated by natural frequencies which are very slow. So slow that it is seen to influence pilot control strategy: pilots often fly large airplanes differently. One reason for this is that the motion is nearly at the pilot's perceptual threshold. Another is that the pilot can now watch the details of the motion evolution which he could not see on faster-responding airplanes. This is an area ripe for further research. Just as Lanchester could not see the short period mode of his glider, and Gough only noticed that it was annoying but researchers in the 1950's and 1960's found ways to exploit this mode of motion, the phasing of the motion degrees of freedom within the modes may well hold some clues for the future. The fact is that when the pilot is flying the airplane, he is never stationary in a mathematical sense. Even when tracking a mathematically stationary signal, the pilot's control response is not stationary. What this means is that the pilot is continuously involved with the transient response.

In the pursuit of economic performance, natural stability is giving way to artificial stability, but there are important clues that, particularly for large, sluggish transports, the specification of frequency and damping alone might not be adequate. The evidence suggests that the augmentation being used produces significantly non-classical dynamic response. And because the airplane is so slow, the pilot can see it, and occasionally reports having difficulty with it.

Nearly all of the simulation of airplane flight dynamics makes use of the quasi-steady aerodynamic assumption, which assumes that when an airplane state changes or when a control is deflected, the aerodynamic force associated with the new condition is achieved instantaneously. This assumption is applied on the basis of another assumption that suggests that differences on the order of a few hundred or so milliseconds will not change the modal frequencies or damping values much. While this is true, there are other handling qualities metrics which are indeed quite sensitive to even a few tens of milliseconds. It was found that the difference in time response due to the quasi-steady aerodynamic assumption is directly proportional to the chord length of the lifting surface. Physically larger surfaces take longer in the time domain to generate aerodynamic force. While the effect is frequency dependent, it has been shown that the effective delay can be in hundreds of milliseconds for very large aircraft.

Much of the educational literature (e.g. textbooks), while many times appropriately pointing out that a rigorous analysis produces actuator forms of second or third order, often provides advice suggesting that first-order approximations are adequate. This assumption has been carried into many research programs as well. The work of Chapter 4 revealed that the consequences of that approximation are not conservative in terms of effective time delay in the transient response. In the case of large airplanes with slow natural frequencies, the effective delay is real, measurable, and adversely affects the handling of the airplane.

The pilot's connection to the airplane is through the manipulator which has its own static and dynamic characteristics. It was seen in Chapter 3 that while the current civil requirements on cockpit feel forces are only via the final airplane response (e.g. stick force/knot or stick force/g) and the less-than-satisfying "without excessive piloting strength or skill" requirement. There is no mention of optima. Where there is qualitative guidance, it is only for the lowest level of acceptable handling. On the military side, the requirements are somewhat more prescriptive and include advice on breakout force, but not friction or damping or the resulting phase delay, except at the whole-airplane level. In the academic arena, Hess (2004) had proposed criteria for controller "linearity".

Hess' Linearity Index was analyzed and found to be too limited to be of direct use, but the concept was found interesting. Two attempts were made to generalize Hess' method, finding that neither of those produced results which could be related to handling qualities.

The feel system has been approached first from a performance-based aspect: combinations of characteristics, friction, breakout, gradient, etc., have been identified and validated. This was done both from a theoretical basis and from a brute-force, ask-the-pilot-if-he-likes-it approach.

By approaching the feel system question via pilot modelling, two missions were accomplished: important insights were gained about how pilots interact with the hardware (e.g. the pilot does not have to adjust the CNS gains in order to work through the control system to get the performance he's after); and a significant new use for these techniques has been exercised.

Finally, new insights have been gained into the mechanism of Pilot Induced Oscillations. Other researchers have identified combinations of characteristics to be avoided, this work has identified a theoretical basis for the instability.

The RTO (nee AGARD) compilation of best practices for flight control system design, written to collect a number of painful lessons learned (Research and Technology Organization., 2000) summarizes the experience of the Task Group:

> "...the PIO frequency can not be too high, the PIO gain cannot be too low, the phase delay can not be too small, that the large amplitude response cannot be linearized too much."

Figure 5-1. Airbus A380 Arrives at OSH

(Photo Courtesy of EAA.)

6 Conclusions

...the way of progress is neither swift nor easy.

Marie Curie*

What is the hardest task in the world? To think.

Ralph Waldo Emerson†

Pilots are firmly rooted in the time domain. They fly the airplane in real time observing signals, signs, and symbols, generating control strategies and manipulating the controls in order to exercise their will over the flight path of the airplane: to close the various control loops as required to make the airplane go where they want it to go. While much effort is expended in the technical community following McRuer's advice to take advantage of the power of linear systems theory, the pilot cannot see the spectrum, and is in general not aware of the frequency at which either inputs are made or responses take shape. What is important to the pilot is what the very large airplane does in the first few seconds after an input is made. The pilot wants to see that the airplane state is changing (e.g. pitch attitude, flight path, etc.), and that it's changing in some rational proportion to his inputs. Predictable responses to the pilot's inputs will over time, allow the pilot to learn input/response relationships and when they might be useful: the pilot can learn to use a pre-cognitive control strategy – as long as the responses are predictable: the response is the same every time.

In the end, the airplane is what it is, and the pilot must deal with it. The focus of this thesis is whether the airplane is what the designer wanted it to be. The answer to that lies in the fidelity of the models employed during the design process and in what the designer does with what the models illuminate. Mathematics is the language of relationships. In the present example, the relationships of interest are between the pilot and the airplane he is trying to control: the airplane handling qualities.

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*Marie Curie was a Polish-French Chemist and physicist who shared in the Nobel Prize for Physics in 1903 and was awarded the Nobel Prize in Chemistry in 1911. (Curie, 1923)

† Ralph Waldo Emerson was an American essayist, lecturer and poet in the 19th century. Emerson (1841)

The principal outcome of the research is the development of an entirely new handling qualities criterion for application to very large transport aircraft. The Dynamic Oversteer Criterion may be used to assess the propensity of the controlled aircraft for PIO events. The criterion has been shown to be easily applied and reliable in its prediction. In addition, significant findings have been made leading to an enhanced understanding of the handling qualities of large transport aircraft. All of the conclusions are summarised below in the context of the original objectives of the research programme.

While the basic dynamic equations of motion for airplanes have been known and understood for some time, it is not clear that there is a widespread understanding of just how these characteristics change as airplanes get larger or the implications to handling qualities.

Objective 1 was to develop and articulate an understanding of the realities of large aircraft dynamic response and the implications for pilot closed loop control, including low frequency modal dynamics, transient response to controls, and relaxed static stability.

It was shown that the primary modal frequencies are comparatively quite slow (7 to 10 second short periods are not uncommon). Moreover, it was shown that as the airplane gets larger, the short period frequency tends towards the phugoid. So not only does the primary inner-loop natural frequency used by the pilot get slower, the separation between the classical phugoid and short period gets smaller. One outward manifestation of this reduction in natural frequency is an observed change in pilot behaviour: from smooth, closed loop control towards a pulse-width modulated bang-bang controller.

As static stability reduced in pursuit of airplane performance (lower drag, lighter weight for smaller tails) the short period is seen to get even slower. If the configuration is allowed to progress to negative static margins, the nature of the motions of the classical short period and phugoid modes were seen to change dramatically. It was seen that care needs to be taken to ensure that when the dynamics are augmented to have modes which have frequency and damping of a traditional short period these augmented modes actually display eigenvectors which look like a short period.

With large airplanes comes a need for powered controls and much analysis conducted in simulation. These simulations rely on mathematical models of various components of the airplane to predict dynamic motions.

Objective 2 was to consider the implications of specific model element forms and make recommendations for their use in handling qualities analysis for large transport aircraft, including the quasi-steady aerodynamic assumption and the order of actuator models used in simulation.

The mathematical modelling techniques for computing aerodynamic forces in flight dynamics simulations has been found to nearly universally employ the quasi-steady aerodynamic assumption that the force generated at a given angle of attack and control surface deflection is generated instantaneously. There is a similarly nearly universal assumption that this is adequate for handling qualities analysis. The physics behind these assumptions has been shown to be a function of airplane size: as airplane dimensions get larger, the time in seconds for the unsteady lift to build gets larger. That is to say that the difference between the assumed temporal lift changes and the real lift changes in time gets larger with larger airplanes. This difference was shown to be on the order of hundreds of milliseconds for large airplanes, which is significant from a handling qualities point of view.

While most authors acknowledge the physics which dictates a second- or third-order model for a hydraulic servo actuator, many suggest a simpler first-order model instead. It has been shown that the assumptions which allow this simplification are not valid for the case of large airplane control actuation. Further, it has been shown that the consequences of using first- instead of higher order models is a non-conservative representation of the dynamics in terms of delay to a pilot’s input. It was shown that the effect is measurable in terms of the handling qualities.

The pilot's access to control of the flight path is via the control system manipulators (whether, sticks, wheel/columns, pedals, or others). With the advent of powered controls also came a need for artificial feel force in the cockpit. Analysis of the relevant requirements identified a deficiency, in design guidance, particularly in terms of specifying nonlinear elements in the system. It was shown that certain nonlinear characteristics are necessary, even desirable, in the presence of inevitable mechanical friction.

Objective 3 was to assess the effects of linearity in the cockpit feel system and develop a method for establishing handling qualities boundaries and develop a set of boundaries for lateral control with a wheel.

One figure of merit identified for evaluation of nonlinear characteristics was Hess' Linearity Index. This was evaluated and shown to have only limited application. Two different attempts were made to extend this concept to eliminate the limitations. Unfortunately, when these results were compared to measured handling qualities ratings, the correlation was not very good.

A new method was developed to predict not only optimum combinations of friction and breakout forces but also to find the boundaries of those combinations between handling qualities levels.

Piloted simulation evaluations were carried out and collected both handling qualities ratings and pilot opinion data over ranges of these characteristics parameters. These measured data represent a truth model and when applied to the analytic method developed, showed good correlation.

While many researchers have made good use of pilot modelling techniques to assess the limits of pilot control of various aircraft, it has been seen that pilot models can also be usefully employed to illuminate the character of the interaction between the pilot and the control system via the feel characteristics.

Objective 4 was to use pilot modelling techniques to develop understanding of the interaction of pilots with the feel characteristics of large aircraft.

Methods have been developed and applied to lateral control of large aircraft with a wheel controller. Piloted simulation experiments were conducted to provide a database of pilot responses to various changes in feel characteristics. Those responses were then analyzed to produce pilot models which are sensitive to the changes in feel characteristics.

One of the most confounding challenges in handling qualities is the dynamic instability of Pilot Induced Oscillations (PIO). It was seen that the industry's understanding of this phenomenon has evolved over the past few decades with significant contributions to understanding just what constitutes the event itself, and what underlying dynamics participate in the event itself. It has been shown that none of these have been able to identify the precursor dynamic characteristics which drive a pilot to the PIO itself.

Objective 5 was to develop and assess a PIO propensity prediction criterion.

A new criterion, Dynamic Oversteer, has been developed on the basis of control theoretic constructs which show that there are conditions, perhaps well before the pilot reaches -180 degrees phase, in which any attempt by the pilot to improve performance by increasing frequency or pilot gain will result in the airplane dynamic response increasing faster than the pilot's input gain increases. Further, it was shown that the pilot's chasing performance in this way will lead to the PIO identified by other criteria. Dynamic Oversteer has been assessed against large airplane characteristics and shown to be successful for both linear and nonlinear cases.

[Note: Dynamic Oversteer and associated technologies is protected by patent.]

7 Recommendations

Honourable errors do not count as failures in science, but as seeds for progress in the quintessential activity of correction.

Stephan Jay Gould*

...truth will sooner come out of error than from confusion.

Sir Francis Bacon†

This work has produced some new insights which are ripe for additional research. In the realm of low frequency dynamics, this thesis has identified the fact that the short period and phugoid modes get closer together with airplane size. This knowledge gives rise to new questions:

- Dedicated handling qualities studies could usefully be carried out to evaluate the limits of the pilot's ability to adapt to those configurations (low frequency primary pitch mode and close phugoid).

Understanding that the presence of unsteady aerodynamics on large airplanes can contribute to phase lags, which are added to those of actuators, feel systems, and other control system elements gives rise to a need further understanding about the relative importance of these elements. This gives rise to the need for a budgeting process. The current requirements discuss total lags and delays, giving no accommodation for where they arise. Proposals should be raised for how these could be allocated.

While relaxing the static stability brings economic benefits, it was shown that the nature of the motion associated with the dominant modes changes at these aft CG conditions. This new knowledge brings questions:

- While eigenstructure assignment has been explored from the point of view of capability, additional work is necessary to understand the handling qualities implications. In particular, starting with a

* Stephan Jay Gould was an American Paleontologist, evolutionary biologist, and historian of science. (Gould, 1998).

† Sir Francis Bacon was English philosopher, statesman, scientist, jurist, orator and author. (Bacon, 1620*).*

relaxed stability bare airframe, a control system could be generated which puts not just the eigenvalues but the eigenvectors back in place. Then the handling qualities of the resulting configuration should be evaluated.

A large part of this thesis was dedicated to understanding effects of the cockpit feel characteristics on the pilot's ability to manoeuvre the airplane. This work was dedicated to the roll axis. Armed with the knowledge gained about the roll axis, additional work is needed:

- Detailed handling qualities studies, including piloted simulations should be carried out to examine the effects of feel system characteristics in the longitudinal axis. In particular, effects on flight path control would be of great interest because, being a further integration away, requires greater pilot workload.
- Detailed handling qualities studies, including piloted simulations should be carried out to examine the effects of feel system characteristics in the directional axis. The pilot's use of pedals is all but ignored in both the literature and in the rest of industry.

REFERENCES

Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft, (2000), ADS-33E-PRF, March, 2000, US Army Aviation and Missile Command, Redstone Arsenal, AL.

A'Harrah, R. (1995), "The Process for Addressing the Challenges of Aircraft Pilot Coupling" in *AGARD Advisory Report No. 335*, Flight Vehicle Integration Panel Workshop on Pilot Induced Oscillations in Turin, Italy, Hull, Quebec, Canada: AGARD.

Abzug, M. J., and Larrabee, E. E., (1997), *Airplane Stability and Control: A History of the Technologies That Made Aviation Possible*, Cambridge, UK: Cambridge University Press.

Abzug, M., and Larrabee, E., (1997), *Airplane Stability and Control: A History of the Technologies that Made Aviation Possible*, Cambridge, UK: Cambridge University Press.

AIAA, (1992), Atmospheric and Space Flight Vehicle Coordinate Systems, Standard ANSVAIAA R-004-1992, Reston, VA, USA: AIAA.

Anderson, J., (1998), A History of Aerodynamics and its Impact on Flying Machines, Cambridge, UK: Cambridge University Press.

Arnold, E.,(2009), PIO Testing of Transport Category Aircraft, Issues and Observations, presented at SETP Annual Meeting, Beverly Hills, CA.

Ashkenas, I. L., (1984),Twenty-Five Years of Handling Qualities Research, AIAA Journal of Aircraft, Vol. 21, No. 5, Reston, VA, USA: AIAA.

Ashkenas, I. L., and Klyde, D. H, (1989), *Tailless Aircraft Performance Improvements with Relaxed Static Stability,* CR-181806, Hampton, VA, USA: NASA.

Babister, A. W., (1980), *Aircraft Dynamic Stability and Response*, Oxford, England: Pergamon Press.

Bachelder, E. N., and Klyde, D., (2003), “Wavelet-Based Analysis of Roll Ratchet using a Flight Test Database”,AIAA-2003-5692, in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, August, 2003, Austin Texas, Reston, VA: AIAA.

Bacon, Francis, (1620),The New Organon (1620) in James Spedding, Robert Ellis and Douglas Heath (eds.), *The Works of Francis Bacon* (1887-1901), Vol. 4, retrieved from http://onlinebooks.library.upenn.edu.

Bailey, R. E., and Knotts, L, H., (1990) *Interaction of Feel System and Flight control System Dynamics on Lateral Flying Qualities*, NASA CR-179*445,* December, 1990, Langley, VA, USA: NASA.

Bartel, J., (2003), *The Influence of Artificial Feel System Dynamics on Aircraft Handling Qualities,* MSc Thesis, Cranfield, UK: Cranfield.

Beddoes, T. S., (1980), “Application of Indicial Aerodynamic Functions”, in *Special Course on Unsteady Aerodynamics*, Rhode-St-Genése, Belgium, March, 1980, London: AGARD.

Bihrle, W., (1966), *A Handling Qualities Theory for Precise Flight Path Control*, AFFDL-TR-65-198, Wright-Patterson AFB, OH, USA: Air Force Flight Dynamics Laboratory.

Boeing Commercial Airplanes, (1980a), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Initial Act Configuration Design Study,* CR159249, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1980b), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Initial Act Configuration Design Study, Summary Report,* CR-3304, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1980c), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Current and Advanced Control System Definition Study Vol II Appendicies,* CR-165631, Hampton, VA, USA: NASA

Boeing Commercial Airplanes, (1980d), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – ACT/Control/Guidance System Study*, CR 165963, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1981a), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Wing Planform Study and Final Configuration Selection, Summary Report,* CR-3468, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1981b), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Project Plan,* CR-3305, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1982a), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Final Act Configuration Evaluation,* CR-3519, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1982b), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Current and Advanced Act Control System Definition Study, Summary Report*, CR-3545. Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1982c), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Demonstration Act System Definition, Final Report,* CR-165920, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1983a), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project –*

Longitudinal Handling Qualities Study of a Relaxed Stability Airplane, CR-3660, Hampton, VA, USA: NASA

Boeing Commercial Airplanes, (1983b), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Test Act System Description, Final Report,* CR-172221, Hampton, VA, USA: NASA.

Boeing Commercial Airplanes, (1983c), *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project – Test Act System Validation, Final Report,* CR-172525. Hampton, VA, USA, NASA.

Boeing Commercial Airplanes, (2012), 747-8 Airplane Characteristics for Airport Planning, D6-583261, December, 2012, at http://www.boeing.com/assets/pdf/commercial/airports/acaps/747_8.pdf, accessed July 20, 2013.

Box, George E. P., and Draper Norman R. (1987). Empirical Model-Building and Response Surfaces, p. 424, New York, NY, USA: Wiley.

Bryan, G., H., (1911), *Stability in Aviation: an Introduction to Dynamical Stability as Applied to Motions of Aeroplanes*, London: Macmillan.

Burnet, C., (1979), *Three Centuries to Concorde*, London: Mechanical Engineering Publications Limited.

Bushgens, G., and Studnev, R., (1979), "*Aircraft Aerodynamics. Dynamics of Longitudinal and Lateral Motion"*, M: Mashinostroeynie. (in Russian)

Campbell, A., (1901), *The Works of George Berkeley, Vol. III: Philosophical Works, 1734-52***,** Oxford: At the Clarendon press. First published in 1744.

Charters, A., (1955), *The Linearized Equations of Motion Underlying the Dynamic Stability of Aircraft, Spinning Projectiles, and Symmetrical Missiles*, NACA TN-3350, Edwards, CA, USA: NACA.

Ciardi, J. A., (1972), *Manner of Speaking,* New Brunswick, New Jersey, USA: Rutgers University Press.

Cook, M., (1994), "The Theory of the Longitudinal Static Stability of the Hang-Glider", in *The Aeronautical Journal*, Vol. 98, No. 978, The Royal Aeronautical Society: London.

Cook, M., (1997), *Flight Dynamics Principles*, 1st Ed., London: Arnold.

Cook, M., (2006), "Modelling the Flight Dynamics of the Hang-Glider", in *The Aeronautical Journal*, January, 2006, The Royal Aeronautical Society: London.

Cook, M., (2007) *Flight Dynamics Principles,* 2nd Ed., Oxford, UK: Elsevier.

Cooper, G., and Harper, R., (1969a), *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, NASA TN D-5153, Washington, DC, USA: NASA.

Cooper, G., and Harper, R., (1969b), *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, AGARD Report 567, London: AGARD.

Cooper, G., and Harper, R., (1984*), Wright Brothers Lectureship in Aeronautics: Handling Qualities and Pilot Evaluation*, AIAA-84-2442, New York, NY, USA: AIAA.

Cotting, C., (2010), *Evolution of Flying Qualities Analysis: Problems for a New Generation of Aircraft***,** PhD Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

Culick, F., (2001), "What the Wright Brothers Did and Did Not Understand About Flight Mechanics – in Modern Terms", AIAA-2001-3385, Reston, VA, USA: AIAA.

Curie, M., (1923), *Pierre Curie*, Tr. Vernon and Charlotte Kellogg, New York, MacMillan, retrieved from: http://web.archive.org/web/20110111210721/http://etext.lib.virginia.edu/etcbin/toccer-new2?id=CurPier.sgm&images=images/modeng&data=/texts/english/modeng/parsed&tag=public&part=front.

Duncan, W. J.,(1952) *The Principles of the Control and Stability of Aircraft*, Cambridge, UK: Cambridge at the University Press,

Efremov, A., Ogloblin, A., Predtechensky, A., and Rodchenko, V., (1992), *The Pilot as a Dynamic System*, M.:Mashinostroyeniye. (in Russian)

Efremov, A., Rodchenko, V., Boris, S., et al, (1996), *Investigation of Pilot Induced Oscillation Tendency and Prediction Criteria Development*, WL-TR-96-3109, Wright Patterson, OH, USA: Wright Laboratory.

Einstein, A., (1930), “What I believe: Living Philosophies XIII” in *The Forum* Vol. LXXXIV No. 4. New York, NY, USA: Forum Publishing Company.

Emerson, Ralph Waldo, (1841), *Essays*, Boston: James Munrowe and Co., retrieved from http://hdl.handle.net/2027/hvd/hvd.ah63va.

Engineering Sciences Data Unit, (1984), *An Introduction to the Time-Dependent Aerodynamics of Aircraft Response, Gusts, and Active Controls*, ESDU Item 84020, Engineering Sciences Data Unit,

Etkin, B., (1959), *Dynamics of Flight Stability and Control*, New York, NY, USA: Wiley.

FAA, (1980), *Flight Training Handbook*, Advisory Circular 61-21A, Washingtion, DC, USA: FAA.

FAA, (2000), *Pilot Certificates, Aircraft Type Ratings*, Advisory Circular 61-89E, Washington, DC, USA: FAA.

FAA, (2002), Title 14, Code of Federal Regulations, Part 25, Airworthiness Standards: Transport Category Airplanes, Amendment 25-108, Washington, DC, USA: FAA.

FAA, (2004), *Airplane Flying Handbook*, FAA-H-8083-3A, Washington D. C., USA: FAA.

FAA, (2012) Flight Test Guide for Certification of Transport Category Airplanes, AC-25.7C, Washington, DC, USA: FAA

Field, E., and Rossitto, K., (1999), *Approach and Landing Longitudinal Flying Qualities for Large Transports based on In-Flight Results*, AIAA-99-4095, Reston, VA, USA: AIAA.

Field, E., von Klein, W., van der Weerd, R., Bennani, S. (2000), "The Prediction and Suppression of PIO Susceptibility of a Large Transport Aircraft", AIAA-2000-3986, Reston, VA, USA: AIAA.

Field, E.,(1995), *Flying Qualitites of Transport Aircraft: Precognitive or Compensatory?*, PhD Thesis, Cranfield University, Cranfield, UK.

Flight Safety Foundation (2001), *Accident Prevention*, Vol. 58, No. 2, February, 2001.

Fossen, T., (1994), *Guidance and Control of Ocean Vehicles*, Chichester, UK: Wiley.

Foyle, D., and Hooey, B. eds., (2008*), Human Performance Modeling in Aviation*, Boca Raton, FL, USA: CRC Press.

Gainer, T., and Hoffman, S., (1972) *Summary of Transformation Equations and Equations of Motion used in Free-Flight and Wind Tunnel and Data Reduction and Analysis*, NASA SP-3070, Washington, DC, USA: NASA.

Gardner, M., and Barnes, J., (1942), *Transients in Linear Systems Studied by the Laplace Transformation*, New York, NY, USA: Wiley.

Gautrey, J., (1998), *Flying Qualities and Flight Control System Design for a Fly-by-Wire Transport Aircraft*, PhD Thesis, Cranfield, UK: Cranfield Univeristy.

Gautrey, J., and Cook, M., (1998), A Generic Control Anticipation Parameter for Aircraft Handling Qualities Evaluation, in: *The Aeronautical Journal*, March, 1998.

Gibb-Smith, C., (2003,) *Aviation: An Historical Survey*, London: NMSI

Gibson, J, and Hess, R. (1997), *Stick and Feel System Design*, AGARD-AG-332, AGARD, Quebec.

Gibson, J. (1999), *Development of a Design Methodology for Handling Qualities*, PhD Thesis, Delft, The Netherlands: University Press.

Gilyard, G., and España, M. (1994) *On the Use of Controls for Subsonic Transport Performance Improvement: Overview and Future Directions*, TM-4605, Edwards, CA, USA: NASA.

Gottzein, E., (2007), "History of the IFAC Technical Committee on Aerospace", available at: http://www-prod-gif.supelec.fr/invi/ifac/history.pdf *(accessed 15 June, 2011).*

Gough, M., Beard, A., (1936), *Limitations of the Pilot in Applying Forces to Airplane Controls*, NACA TN-550, Langley, VA, USA: NACA.

Gould, Stephen Jay, (1998), *Leonardo's Mountain of Clams and the Diet of Worms: Essays on Natural History*, New York: Harmony.

Graham, D., and McRuer, D. T., (1961) *Analysis of Nonlinear Control Systems,* New York, USA: Wiley.

Grantham, W. D., Person, L. H. Jr., Brown, P. W., Becker, L. E., Hunt, G. E., Rising, J. J., Davis, W. J., Willey, C. S., Weaver, W. A., and Cokeley, R., (1985), *Handling Qualities of a Wide-Body Transport Airplane Utilizing Pitch*

Active Control System (PACS) for Relaxed Static Stability Application, TP-248, Hampton, VA, USA: NASA.

Grantham, W., Smith, P., Deal, P., and Neely, W., (1984), *Simulator Study of Flight Characteristics of Several Large, Dissimilar, Cargo Transport Airplanes During Approach and Landing*, NASA TP-2357, Langley, VA, USA: NASA.

Gray, W. (2004), *Boundary-Escape Tracking: A New Conception of Hazardous PIO*, United States Evaluation Technical Report PA-04179, Edwards, CA, USA: USAF Test Pilot School.

Guinn, W. A., (1982), *Development and Flight Evaluation of an Automated Stability Active Controls Concept,* CR-165951, Hampton, VA, USA: NASA.

Guinn, W. A., (1983), *Development of an Advanced Pitch Active Controls System and a Reduced Area Horizontal Tail for a Wide Body Jet Aircraft – Executive Summary*, CR-177283, Hampton, VA, USA: NASA.

Guinn, W. A., Rising, J. J., and Davis, W. J., (1984), *Development of an Advanced Pitch Active Control System for a Wide Body Jet Aircraft,* CR-172277, Hampton, VA, USA: NASA.

Guinn, W. A., Willey, C. S., and Chong, M., G., (1983), *Extended Flight Evaluation of a Near-Term Pitch Active Controls System,* CR-172266, Hampton, VA, USA: NASA.

Hancock, G., (1980), "Role of Unsteady Aerodynamics in Aircraft Response", in *Special Course on Unsteady Aerodynamics*, AGARD Report No. 679, Rhode-St-Genése, Belgium, March, 1980, London, UK: AGARD.

Hancock, G., (1995), An Introduction to the Flight Dynamics of Rigid Aeroplanes, Hemel Hemstead, Great Britain, Ellis Horwood.

Heffley, R., and Jewell, W., (1972), *Aircraft Handling Qualities Data*, STI Technical Report 1004-1, May, 1972, Hawthorne, CA: Systems Technology, Inc.

Hess, R., (1979), A Rationale for Human Operator Pulsive Control Behavior, AIAA Journal of Guidance and Control, Vol. 2., No., 3, Reston, VA, USA: AIAA.

Hess, R., (2004) Handling Qualities and Flight Safety Implications of Rudder Control Strategies and Systems in Transport Aircraft, in *AIAA Atmospheric Flight Mechanics Conference*, 16-19 August, 2004, Providence, RI, Reston, VA, USA: AIAA.

Hiltner, D., and Lee, B. P., (2007) “Methods and Systems for Analyzing System Operator Coupling Susceptibility”, US Patent No. 7272473, 18 Sept, 2007, USA.

Hodgkinson, J .(c.2003), personal communication.

Hodgkinson, J. (1998), *Aircraft Handling Qualities*, Reston, VA, USA: AIAA.

Hoh, R., (1990), *Lessons Learned Concerning the Interpretation of Subjective Handling Qualities Pilot Rating Data*, AIAA-90-2824, Reston, VA, USA: AIAA.

Hoh, R., and Michell, D., (1982), *Flying Qualities of Relaxed Static Stability Aircraft, Volume I*, Report TR-1178-1-I, Atlantic City, NJ, USA: FAA.

Hoh, R., and Mitchell, D., (1996), “Handling Qualities Specification – a Functional Requirement for the Flight Control System”, in Tischler, M., ed. *Advances in Aircraft Flight Control*. London, UK: Taylor & Francis Ltd, pp. 3-33

Hoh, R., Mitchell, D., and Hodgkinson, J., (1982), “Bandwidth – a Criterion for Highly Augmented Airplanes”, in *Criteria for Handling Qualities of Military Aircraft*, AGARD-CP-333, London: AGARD.

Hopkin, H., (1966), *A Scheme of Notation and Nomenclature for Aircraft Dynamics and Associated Aerodynamics*, RAE Technical Report 66200.

Hosman, R., (1996), Pilot's Perception and Control of Aircraft Motions, PhD Thesis, Delft University of Technology, The Netherlands: University Press.

Ilupotaife, O. (1997), *Minimizing Pilot-Inuced Oscillation Susceptibility During C-17 Development*. AIAA-97-3497, Reston, VA, USA: AIAA

Ilupotaife, O., Svoboda, G., and Bailey, T. M. (1996), *Handling Qualities Design of the C-17A for Receiver-Refueling*. AIAA-1996-3746, Reston, VA, USA: AIAA.

Jagacinski, R, and Flach, J., (2003), *Control Theory for Humans: Quantitative Approaches for Modeling Performance*, Mahwah, NJ, USA: Lawrence Erlbaum.

Johnston, J. F., et. a. (1979), *Accelerated Development and Flight Evaluation of Active Controls Concepts for Subsonic Transport Aircraft – Volume I – Load Alleviation/Extended Span Development and Flight Test,* CR-159097, Hampton, VA, USA: NASA.

Kern, T., (1996), *Redefining Airmanship*, New York, NY, USA: McGraw-Hill

Kotik, M., (1971), Short *Course of Engineering Psychology*, Tallinn: Valgus.

Latham, A., (1956), *Hand Operated Control Forces*, Human Engineering Bulletin 56-5H, New York, NY, USA: Flight Safety Foundation.

Lee, B. P., (1988), *Review of Aerodynamic Control Surface* Design IAR Report 88-126, Wichita State University, Wichita, KS, USA: Institute for Aviation Research.

Lee, B. P., (1990), *Prediction Methodologies for Nonlinear Aerodynamic Characteristics of Control Surfaces*, MSc Thesis, NAIR Report 90-17, Wichita State University, Wichita, KS, USA.

Lee, B. P., (1997) “Design and Use of a Standard Manoeuvre Set in Piloted Simulation for Lateral Handling Qualities Criteria Development”, in: *Flight Simulation – Expanding the Boundaries*, Conference Proceedings, May, 1997, The Royal Aeronautical Society, London, England: RAeS.

Lee, B. P., (2000a), “Recent Experience in Flight Testing for Pilot Induced Oscillations (PIO) on Transport Aircraft”, ICAS-0691, in: ICAS 2000 Congress, Harrogate, England.

Lee, B. P., (2000b), “Recent Experience in Flight Testing for Pilot Induced Oscillations (PIO) on Transport Aircraft”, *Aeronautical Journal*, August, 2000, London, England: RAeS.

Lee, B. P., (2001), “PIO Flight Test Experience at Boeing (Puget Sound) – and the Need for More Research”,(Invited), in Shafer, M., and Steinmetz, P., *Pilot-Induced Oscillation Research: Status at the End of the Century*, NASA CP-2001-210389 Vol. 1 and 2, Edwards, CA, USA: NASA.

Lee, B., (2007), *Applications of High Fidelity Simulation at Boeing Commercial Airplanes*, lecture to SIMONA Symposium, Fidelity in Motion, Delft University of Technology, 29 March, 2007, Delft, The Netherlands: TU Delft.

Lee, B., Rodchenko, V., and Zaichik, L., (2003) “Effect of Wheel System Characteristics on Aircraft Handling Qualties”, AIAA 2003-5310, in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Austin Texas, August, 2003, Reston, VA, USA,: AIAA.

Lee, B., Rodchenko, V., Zaichik, L., (2004), “An Approach to Feel System Characteristics Selection”, AIAA-2004-2362 in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Providence, RI, August, 2004, Reston, VA, USA: AIAA.

Lee, B., Rodchenko, V., Zaichik, L., and Yashin, Y.,(2005), “Effect of Pedal Feel System Characteristics on Aircraft Handling Qualities”, AIAA-2005-

6034, in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, San Francisco, CA, August, 2005, Reston, VA, USA: AIAA.

Lippmann, W., (1920), *Liberty and the News*, New York, NY, USA: Harcourt, Brace, and Howe.

Mathews, C., Talmage, D., and Witten, J., (1951), *Effects on Longitudinal Stability and Control Characteristics of a B-29 Airplane of Variations of Stick-force and Control-Rate Characteristics Obtained Through use of a Booster in the Elevator-Control System*, NACA TN 2238, Langley, VA, USA: NACA.

McAvoy, W., (1937), *Maximum Forces Applied by Pilots to Wheel-Type Controls*, NACA TN-623, Langley, VA, USA: NACA.

McElhone, J., (2004), *Application of Modern Handling Qualites Metrics to Artificial Feel System Dynamics*, MSc Thesis, Cranfield, UK: Cranfield.

McFarland, R., (1975), *A Standard Kinematic Model for Flight Simulation at NASA-Ames*, NASA CR-2497, Langley, VA, USA: NASA.

McLean, D., (1990), *Automatic Flight Control Systems*, Hemel Hempstead, UK: Prentice Hall.

McRuer, D. T., et al, (1997), Aviation Safety and Pilot Control: Understanding and Preventing Unfavourable Pilot-Vehicle Interactions, National Academy Press, Washington, DC, USA.

McRuer, D., (1983), Progress and Pitfalls in Advanced Flight Control Systems, in *Advances in Guidance and Control Systems*, AGARD CP 321, Loughton, UK: AGARD.

McRuer, D., (1995), *Pilot Induced Oscillations and Human Pilot Behavior*, NASA CR-4386, Edwards, CA, USA: NASA Dryden Flight Research Center.

McRuer, D., (1995), *Pilot-Induced Oscillations and Human Dynamic Behavior*, NASA CR-4683, Edwards, CA,. USA: NASA.

McRuer, D., Ashkenas, I., and Graham, D., (1973), Aircraft Dynamics and Automatic Control, Princeton, NJ: Princeton University Press.

McRuer, D., Krendel, E., (1974), *Mathematical Models of Human Pilot Behaviour*, AGARDograph No. 188, Paris, FR: AGARD.

McRuer, D., Myers, T., (1982), *Flying Qualities of Relaxed Static Stability Aircraft, Volume II*, Report TR-1178-1-I, Atlantic City, NJ, USA: FAA.

Mitchell, D., and Klyde, D., (1998), "A Critical Examination of PIO Prediction Criteria", AIAA-98-4335, Reston, VA, USA: AIAA.

Mitchell, D., Hoh, R., (2000), *Development of Methods and Devices to Predict and Prevent Pilot-Induced Oscillations*, VA-WP-TR-2000-3046, Wright-Patterson, OH USA: US Air Force Research Lab.

Mitchell, D., Hoh, R., Aponso, B., (1994), Proposed Incorporation of Mission-Oriented Flying Qualities into MIL-STD-1797A, WL-TR-94-3162, Wright-Patterson AFB, OH, USA: US Air Force.

Mitchell, D., Klyde, D. (2004), "Recommended Practices for Exposing Pilot-Induced Oscillations or Tendencies in the Development Process", AIAA 2004-6810, presented at *USAF Developmental Test and Evaluation Summit*, November 2004, Woodland Hills, CA, Reston, VA: AIAA.

Mitchell, D., Klyde, D., (2005) "Testing for Pilot-Induced Oscillations", AIAA 2005-5811, in *AIAA Atmospheric Flight Mechanics Conference and Exhibit, San Francisco*, CA, August, 2005, Reston, VA: AIAA.

Mitchell, D., Klyde, D. (2006), "Identifying a PIO Signature – New Techniques Applied to an Old Problem", AIAA-2006-6495, in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Keystone, CO, August, 2006, Reston, VA: AIAA.

Mitchell, D., Klyde, D. (2008), **"**Identifying a Pilot-Induced Oscillation Signature: New Techniques Applied to Old Problems", *Journal of Guidance, Control, and Dynamics*, Vol. 31, No. 1, pp 215-224, Reston, VA: AIAA.

Mooij, H., de Boer, W., van Gool, M., (1979*), Determination of Low Speed Longitudinal Manoeuvring Criteria for Transport Aircraft with Advanced Flight Control Systems*, NLR Technical Report TR 79127U, Amsterdam, The Netherlands: NLR.

Morgan, J. M., (1991), "An Initial Study into the Influence of Control Stick Characteristics on the Handling Qualities of a Fly-By-Wire Helicopter", *Flying Qualities*, AGARD CP-508, February, 1991.

Myers, T., McRuer, D., and Johnston, D., (1984), *Flying Qualities and Control System Characteristics for Superaugmeneted Aircraft*, NASA CR-170419, Edwards, CA, USA: NASA.

NACA (1916), First Annual Report of the National Advisory Committee for Aeronautics, Washington: Government Printing Office.

NACA (1917), Nomenclature for Aeronautics, Report No. 9, NACA-TR-9 in Second Annual Report of the National Advisory Committee for Aeronautics, Washington: Government Printing Office.

National Research Council (1997), *Aviation Safety and Pilot Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions*. Washington D. C., USA: National Academy Press.

Newell, F., and Campbell, G., (1954), *Flight Evaluation of Variable Short-Period and Phugoid Characteristics in a B-26*, WADC Technical Report 54-594, Wright Patterson AFB, OH: Air Force Flight Dynamics Laboratory.

Newton, I., (1675-6), cited in Brewster, D., "The Newton Project, Chapter VI", available at http://www.newtonproject.sussex.ac.uk/view/texts/normalized/OTHE00101 , (accessed 23 November, 2011).

Nomoto, K., Taguchi, T., Honda, K., Hirano, S, (1957), On the Steering Qualities of Ships*, International Shipbuilding Progress*, Volume 4, No. 35, pp. 354-370.

Norair, (1953), The Artificial Feel System, Bu Aer Report AE-61-4 V, Washington, DC, USA: Bureau of Aeronautics, Navy Department.

Norair, (1954), *The Human Pilot*, Bu Aer Report AE-61-4 III, Washington, DC, USA: Bureau of Aeronautics, Navy Department.

NTSB (1993), *Aircraft Accident Report: Inadvertent In-Flight Slat Deployment China Eastern Airlines Flight 583 McDonnell Douglas MD-11, B2171, 950 Nautical Miles South of Shemya, Alaska, April 6, 1993.* Washington, DC, USA: NTSB.

Ossoli, Sarah Margaret Fuller, (1852), “Notes from Cambridge, Massachusetts”, in *Memoirs of Margaret Fuller Ossoli*, Vol. II, Boston, MA, USA: Phillips, Sampson

Parks, D., (2009), “How Do I Control This Thing”, in *General Aviation News*, May 8, 2009, Tacoma, WA, USA: Flyer Media.

Pavel, M., Yilmaz, D., Smaili, H., Desyatnik, P., Jones, M. (2010), *Deliverable No. D1.1: Background, Definition, and Classification of A/RPC, Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection* ARISTOTEL. Delft, The Netherlands: TU Delft.

Perkins, C., (1970), “Development of Airplane Stability and Control Technology”, von Karman Lecture, *Journal of Aircraft*, Vol. 7 No. 4, Reston, VA, USA: AIAA.

Rasmussen, J., (1983), “Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models”, in *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-13, no.3.

Raymond, E., and Chenoweth, C, (1993), *Automatic Flight Control Actuation System Design*, Warrendale, PA, USA: Society of Automotive Engineers,

Research and Technology Organization, (2000), *Flight Control Design – Best Practices*, RTO Technical Report TR-029, Neuilly-sur-Seine, France: RTO.

Rodchenko, V., Zaichik, L, Yashin, Y., Perebatov, V., and Lyasnikov, V.,(1994b) *Investigation of Controllabilitiy Criteria of Unmaneuverable Aircraft Equipped with a Side Stick*, Report SPC-93-4046, Zhukovsky, Russia: Central Aero-Hydrodynamic Institute.

Rodchenko, V., Zaichik, L., Yashin, Y., (1996) *Similarity Criteria and Some Requirements to Feel System Modelling*, AIAA-96-3334, Reston, VA, USA: AIAA.

Rodchenko, V., Zaichik, L., Yashin, Y., (1998) "Similarity Criteria for Manipulator Loading and Control Sensitivity Characteristics", in *Journal of Guidance Control, and Dynamics*, Vol. 21, No. 2, March-April, 1998.

Rodchenko, V., Zaichik, L., Yashin, Y., Lyasnikov, V., Galyuchenko, A., Rofov, I., (1995) *Investigation of Feel System and Control Sensitivity Characteristics Influencing P-I-O of Unmaneuverable Aircraft*, Report SPC-94-4027, Zhukovsky, Russia: Central Aero-Hydrodynamic Institute.

Rodchenko, V., Zaichik, L., Yashin, Y., Perebatov, V., and Lyasnikov, V., (1994a) *Investigation of Controllability Criteria of Class III Aircraft Equipped with a Sidestick*, WL-TR-96-3079, Wright-Patterson Air Force Base, OH, USA: Flight Dynamics Directorate, USAF.

Roskam, J. (1979b), Airplane *Flight Dynamics and Automatic Flight Controls, Part II*, Ottawa, KS, USA: Roskam.

Roskam, J. (1986), *Airplane Design, Part IV: Layout Design of Landing Gear and Systems*, Ottawa, KS, USA: Roskam.

Roskam, J., (1979a), *Airplane Flight Dynamics and Automatic Flight Controls, Part I*, Ottawa, KS: Roskam.

Russell, B., (1920), *Marriage and Morals*, London: George Allen and Unwin.

Schmidt, D., (2012), *Modern Flight Dynamics*, New York, NY, USA: McGraw-Hill.

Schuler, J. (1986), Research Challenges in Flying Qualities Criteria for Transport Aircraft Flight Control Systems, presented at 1986 *Workshop of Flying Qualities Research Challenges*, NASA-Langley Research Center, Hampton VA, Boeing Document D180-30236-1.

Schuler, J. M. (1983) “New Flying Qualities Criteria for Relaxed Static Longitudinal Stability”, in *AIAA Atmospheric Flight Dynamics Conference*, August, 1983, Gatlinburg, Tennessee, Reston, VA, USA,: AIAA.

Shomber, H., and Gertsen, W., (1967), Longitudinal Handling Qualities Criteria: An Evaluation, in *AIAA Journal of Aircraft*, Volume 4, July-August, 1967, New York, NY, USA: AIAA.

Silvestrov, M, Koziorov, L, Ponomarenko, V., (1986), *Automation in Aircraft Control with Regard to Human Factor*, Moscow: Mashinostroenie.

Sizlo, R. A., Berg, R. A., and Gilles, D. L., (1979), *Development of a Low-Risk Augmentation System for an Energy Efficient Transport Having Relaxed Static Stability,* CR-159166, Hampton, VA, USA: NASA.

Sliwa, S., (1980), *Economic Evaluation of Flying-Qualities Design Criteria for a Transport Configured with Relaxed Static Stability,* TP-1760, Hampton, VA, USA: NASA.

Smith, R. E., (1978), Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities, AFFDL-TR-78-122, Wright Patterson AFB, OH, USA: USAF.

Smith, R., and Sarrafian, S., (1986), Effect of Time Delay on Flying Qualities: an Update, in *,Journal of Guidance, Control, and Dynamics, Vol9, No. 5, Sept.-Oct., 1986*, New York, NY, USA: AIAA.

Soulè, H., (1936), *Flight Measurements of Dynamic Longitudinal Stability of Several Airplanes, and a Correlation of the Measurements with Pilots' Observations of Handling Characteristics*, NACA Report 578, Washington, DC, USA: NACA.

Stapleford, R. L., Craig, S. J., and Tenant, J. A., (1969), Measurement of Pilot Describing Functions in Single-Controller Multiloop Tasks", NASA CR-1238, January, 1969, Washington, DC, USA: NASA.

Stengel, R., (2004), *Flight Dynamics*, Princeton, NJ, USA: Princeton University Press.

Student, Captain, (1923), from Technische Berichte, Volume III, No. 6, P pp. 185-187 (1918) quoted in "Flight Characteristics", NACA TN-153, August, 1923, Washington, DC, USA: NACA.

Stuurman, A. M., (1969), Modelling the Helmsmen: A Study to Define a Mathematical Model Describing the Behaviour of a Helmsman Steering a Ship Along a Straight Course, Delft, Inst. TNO for Mech. Constr., 1969, No. 4701, Delft, the Netherlands.

Sutton, R., (1990), Modelling Human Operators in Control System Design, Research Studies Press, Ltd.,

Sutton, R., Roberts, G., and Mort, N.,(1990), *A Review of Warship motion Control Research Undertaken at RNEC Manado*n, London, UK: The Institute of Marine Engineers.

Tennyson, Baron Alfred, (1842) Locksley Hall, in The Poetical Works of Alfred Tennyson, Cambridge: Houghton, Mifflin and Company.

Thompson, P., M., Bachelder, E., N., Klyde, D., Harris, C., Brenner, M., (2004), "Wavelet-Based Techniques for Improved On-Line Systems Identification, AIAA 2004-6838, in *USAF Developmental Test and Evaluation Summit*, November, 2004, Woodland Hills, CA, Reston, VA: AIAA.

Thompson, P. M., Klyde, D., and Brenner, M. J., (2001), "Wavelet-Based Time-Varying Human Operator Models",AIAA-2001-4009 in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, August, 2001, Montreal, Canada, Reston VA: AIAA.

Tocu, V., Charalabakis, J. and Cohen-Nir, D., (2000) *Final Report on the Accident of the Falcon 900B registered SX-ECH 14 September, 1999,* Report No. 711*,* Romania Ministry of Transport, Civil Aviation Inspectorate, Bucharest.

Urie, D. M., et. al., (1979), *Accelerated Development and Flight Evaluation of Active Controls Concepts for Subsonic Transport Aircraft – Volume II – Aft C.G. Simulation and Analysis,* CR-159098, Hampton, VA, USA: NASA.

US Department of Defense. (1997), Military Handbook, Flying Qualities of Piloted Aircraft, MIL-HDBK-1797, Washington, D. C., USA: US Department of Defense.

van der Vaart, J. C., (1985) "Effects of Aerodynamic Lags on Aircraft Responses", in ,AGARD Conference Proceedings No. 386, Göttingen, Germany, May, 1985, Essex, UK: AGARD.

van der Weerd, R., (2000), *Pilot-Induced Oscillation Suppression Methods and their Effects on Large Transport Aircraft Handling Qualities*, Delft, The Netherlands: Delft University Press.

van Paassen, R., (1994*),Biophysics in Aircraft Control: A model of the neuromuscular system of the pilot's arm*, PhD Thesis, Delft, The Netherlands: van Paassen.

Veldhuyzen, W., (1976), *Ship Manoeuvring Under Human Control: Analysis of the Helmsman's Control Behaviour*, PhD Thesis, TU Delft, The Netherlands: Delft.

Veldhuyzen, W., and Stassen, H.,(1977), The Internal Model Concept: An Application to Modelling Human Control of Large Ships, in Human Factors, Volume 19, No. 4, pp. 367-380.

Vincenti, W., (1988), "How did it Become Obvious that Airplanes Should be Stable?", *American Heritage of Invention and Technology* 4, (Spring/Summer, 1988), pp50-56.

Vincenti, W., (1990), *What Engineers Know and How They Know it: Analytical Studies from Aeronautical History*, Baltimore, MD, USA: Johns Hopkins University Press.

Watson, D. C., Schroeder, J. A., (1990), Effects of Stick Dynamics on Helicopter Flying Qualities", AIAA-90-3477-CP, in *AIAA Guidance, Navigation and control Conference*, Aug, 1990, Reston, VA, USA: AIAA.

Weingarten, N., and Chalk, C., (1981), *In Flight Investigation of Large Airplane Flying Qualities for Approach and Landing*, AFWAL-TR-81-3118, Wright-Patterson AFB, OH, USA: Air Force Wright Aeronautical Labs.

Wickens, C., and Hollands, J., (1999), *Engineering Psychology and Human Performance*, Third Ed., Upper Saddle River, NJ, USA: Prentice Hall.

Zaichik, L., Lyasnnikov, V., Perebatov, V., Rodchenko, V., Saulin, V.,(1990) "Method to Evaluate Optimum Roll Control Sensitivity of Nonmaneuverable Aircraft Equipped with a Wheel", *TsAGI Transactions*, Issue 2477, Zhukovsky, Russia: TsAGI (in Russian).

Zyskowski, M., (2003), "Aircraft Simulation Techniques used in Low-Cost, Commercial Software", AIAA 2003-5818, in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, August, 2003, Austin Texas, Reston, VA, USA: AIAA.

Appendix A The Ubiquitous Second Order Problem

Many authors have pointed out that the solution to a second order differential equation is quite useful in the study of dynamics, and this is certainly true in the study of flight dynamics. Therefore, it is useful to spend some effort to understand just what that equation and its solution means.

Just as many authors see the benefit, many authors begin with the classical spring-mass-damper problem, as in Figure A-1. One clearly written description is that of Cook (1997, 2007). The motion of the mass can be described by

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t) \qquad \text{(A.1)}$$

In which x(t) is the displacement of the mass, c represents the viscous damping, k represents the spring constant or the stability term, and f(t) represents a driving or applied force.

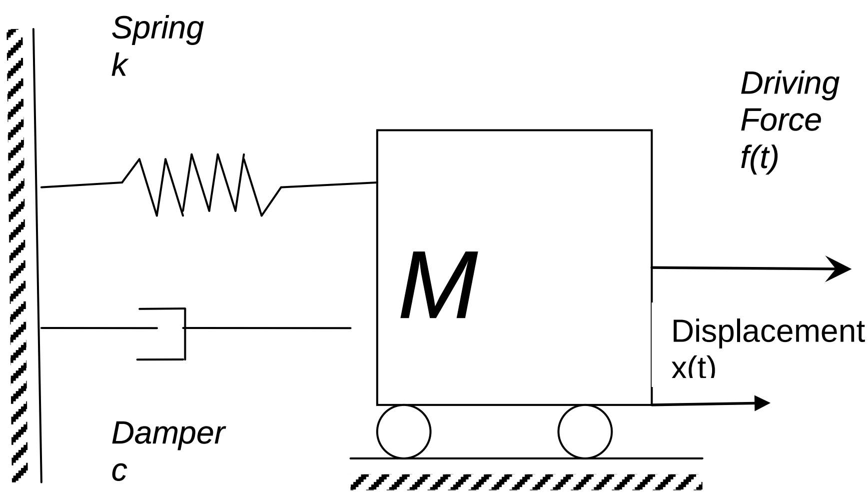


Figure A-1. Classic Spring-Mass-Damper

The classical transient or unforced response is found by setting f(t)=0 so that

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=0 \tag{A.2}$$

And initial conditions can be defined. Cook chooses initial velocity and acceleration $\dot{x}=\ddot{x}=0$ and initial position x=A. The time response of this system, subject to those initial conditions can be found using the Laplace transform.

$$\begin{aligned}&\mathscr{L}\{m\ddot{x}(t)+c\dot{x}(t)+kx(t)\}\\&=m(s^2x(s)-sx(0)-\dot{x}(0))+c(sx(s)-x(0))+kx(s)\\&=m(s^2x(s)-sA)+c(sx(s)-A)+kx(s)=0\end{aligned} \tag{A.3}$$

After invoking the definitions

$$\frac{k}{m}={\omega_n}^2 \quad \text{and} \quad \frac{c}{m}=2\zeta\omega_n \tag{A.4}$$

in which ω_n represents the system undamped natural frequency and ζ represents the system damping ratio, or in some circles “dimensionless damping”, arriving at

$$x(s)=\frac{A(s+2\zeta\omega_n)}{(s^2+2\zeta\omega_n s+{\omega_n}^2)} \tag{A.5}$$

(The use here of the subscript “n” on ω to remind the “natural” frequency everywhere is perhaps an American thing. Similarly, the damped frequency will carry a subscript “d”, not to be confused with the Dutch roll frequency, also denoted by ω_d by many authors. It is noted that Cook’s standard of using ω with no subscript for the natural frequency and ω_n for the damped natural frequency makes a lot of sense as long as it is remembered that the unsubscripted frequency is the natural one.)

At this point, the time domain solution can be found by finding the inverse Laplace transform of equation A.5. This is facilitated by first factoring the denominator and splitting into partial fractions and invoking the appropriate Laplace transform pair to finally arrive at

$$x(t) = \frac{Ae^{-\zeta\omega_n t}}{2}((1+\frac{\zeta}{\sqrt{\zeta^2-1}})e^{-\omega_n t\sqrt{\zeta^2-1}} + (1-\frac{\zeta}{\sqrt{\zeta^2-1}})e^{\omega_n t\sqrt{\zeta^2-1}}) \tag{A.6}$$

This is the general form of the solution giving the unforced motion. The character of the response depends on the value of the damping ratio, ζ.

For the case of $\zeta = 0$, the solution of A.6 becomes

$$x(t) = \frac{A}{2}(e^{-j\omega_n t} + e^{j\omega_n t}) = A\cos\omega_n t \tag{A.7}$$

where $j = \sqrt{-1}$.

This describes a neutrally stable system.

For the case $0 < \zeta < 1$, equation A.6 is modified by substituting

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \tag{A.8}$$

To allow

$$x(t) = Ae^{-\zeta\omega_n t}(\cos\omega_d t - \frac{\zeta\omega_n}{\omega_d}\sin\omega_d t) \tag{A.9}$$

which describes damped harmonic motion.

When $\zeta = 1$, the coefficients of the exponential terms in equation A.6 become infinite. Nevertheless, it can be shown that the damped frequency ω_d goes to zero and the solution becomes

$$x(t) = Ae^{-\omega_n t}(1-\omega_n t) \tag{A.10}$$

Finally, for the case $\zeta > 1$ the solution becomes exponentially convergent and is given by equation A.6 directly.

Cook then wraps up the discussion with a “Summary of a Stable System” in which the roots of the characteristic equation are given as well as a description of the type of time response to be expected:

Damping Ratio	Roots of Characteristic Equation	Type of Response
$\zeta = 0$	$(s + j\omega_n)(s - j\omega_n) = 0$ Complex with zero real component	Undamped sinusoidal oscillation with frequency ω_n
$0 < \zeta < 1$	$(s + \zeta\omega_n + j\omega_d)(s + \zeta\omega_n - j\omega_d) = 0$ Complex with non-zero real component	Damped sinusoidal oscillation with frequency $\omega_d = \omega_n\sqrt{1-\zeta^2}$
$\zeta = 1$	$(s + \omega_n)^2 = 0$ Repeated real roots	Exponential convergence $e^{-\omega_n t}(1-\omega_n t)$
$\zeta > 1$	$(s + r_1)(s + r_2) = 0$ In which $r_1 = \omega_n(\zeta + \sqrt{\zeta^2 - 1})$ $r_2 = \omega_n(\zeta - \sqrt{\zeta^2 - 1})$	Exponential convergence of form $k_1 e^{-r_1 t} + k_2 e^{-r_2 t}$

Table A-1 Summary of Stable System Roots
Adopted from Cook (2007)

Cook goes on to point out that while the classical spring-mass-damper is always stable, airplanes are not always so well behaved.

Appendix B   Handling Qualities Levels

As discussed in Section 3.2.1, although the military and civilian approach to requirements is very different, they are tied together via the concept of Handling Qualities Levels.

Taken directly from the MIL-HDBK-1797 (US Department of Defense, 1997).

> "The handling characteristics described in this standard are specified in terms of qualitative degrees of suitability and Levels. The degrees of suitability are defined as:
>
> Satisfactory: Flying qualities clearly adequate for the mission Flight Phase. Desired performance is achievable with no more than minimal pilot compensation.
>
> Acceptable: Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
>
> Controllable: Flying qualities such that the aircraft can be controlled in the context of the mission Flight Phase, even though pilot workload is excessive or mission effectiveness is inadequate, or both. The pilot can transition from Category A Flight Phase tasks to Category B or C Flight phases, and Category B and C Flight Phase tasks can be completed.
>
> Level 1 is Satisfactory, Level 2 is Acceptable and Level 3 is Controllable. In the presence of higher intensities of atmospheric disturbances, [requirement] 4.9.1 states the relationship between Levels and qualitative degrees of suitability. Where possible, the flying qualities requirements are stated for each Level in terms of limiting values of one or more parameters. Each value, or combination of values, represents a minimum condition necessary to meet one of the three Levels of acceptability.
>
> It should be noted that Level 3 is not necessarily defined as safe. This is consistent with the Cooper-Harper rating scale: for Cooper-Harper ratings of 8 and 9, controllability may be in question. If safe characteristics are required for Level 3, then action must be taken to improve aircraft flying qualities." (p. 85)

It is important to keep these definitions in mind, particularly for the case of rare or failure conditions. It is also important to heed the note above that the specifications are in terms of limiting conditions required to allow a particular level of handling. For example, if the specification requires a particular parameter value for “Level 1”, that defines the boundary between Level 1 and Level 2. Similarly, a “Level 2” value defines the boundary between Level 2 and Level 3. That begs the question; What about a “Level 3” value? What this means is that the specified value is required for handling to be just inside Level 3. While there is no “Level 4” given directly, reference to the Cooper-Harper rating scale indicates that Cooper-Harper ratings worse than 9 result in a loss of control. In this regard, while a rating worse than Level 3 implies a certain loss of control, the other very important detail above is the fact that Level 3 does *not* imply safety, either.

As noted in the text, it becomes important, then that the evaluation pilots are thoroughly trained in the use of both of these means of finding compliance. Since the element that ties them together is process related to proper application of the Cooper-Harper Handling Qualities rating, thorough understanding of that is critical as well.

Appendix C Requirements on Dynamics

For civilian certification, the requirement for longitudinal dynamic stability is in 14CFR25.181 (cited at amendment 25-108 (2002)).

> 25.181 Dynamic Stability
>
> (a) Any short period oscillation, not including combined lateral-directional oscillations, occurring between 1.13 VSR and maximum allowable speed appropriate to the configuration of the airplane must be heavily damped with the primary controls—
>
> (1) free; and
>
> (2) in a fixed position.

The phugoid itself is not mentioned specifically, but, the general paragraph 25.171 specifies:

> 25.171 General
>
> The airplane must be longitudinally, directionally, and laterally stable in accordance with the provisions of Secs. 25.173 through 25.177. In addition, suitable stability and control feel (static stability) is required in any condition normally encountered in service, if flight tests show it is necessary for safe operation.

It is the second sentence of 25.171 which would be cited if an evaluation pilot wanted to draw attention to a phugoid characteristic.

In contrast, the military specifications delineate not only what is required for safe operation, but those characteristics for best handling. Regarding the phugoid, the MIIL-HDBK specifies:

> "Any oscillation with a period of 15 seconds or longer shall have the following damping [below]. Except as may be provided in [other sections], no aperiodic flight path divergence is allowed within the Service Flight Envelope for any Level of flying qualities.
>
> Level 1: equivalent $\zeta_p > 0.04$
>
> Level 2: equivalent $\zeta_p > 0$

Level 3: $T_2 \geq 55$ seconds"

When reading and interpreting these, it is important to remember that phugoid damping of 0.04 represents the boundary between Level 1 and Level 2, that is the boundary between ability to achieve desired performance and the availability of merely adequate performance. The level of phugoid damping equal to zero represents the boundary between Level 2 and Level 3, between "acceptable" and "controllable", between where adequate performance is available (with elevated workload) and Level 3, where safety cannot be assured. Damping levels worse than a time-to-double of 55 seconds represents characteristics which are worse than Level 3.

Regarding the short period dynamic characteristics, as a result of considerable research conducted since the 1960's, there is a profusion of potential criteria and associated requirements, and this is reflected in the MIL-HDBK's guidance. Preferred is the Control Anticipation Parameter, which had its origins in (Bihrle, 1966). Various alternate formulations have been used for various purposes, notably, the Steady Manoeuvring Force and Pitch Sensitivity Criterion (SMFPSC) Extension to the CAP Criterion of NLR (Mooij, de Boer, and van Gool, 1979) and the Cranfield Generic CAP (GCAP) (Gautrey and Cook, 1998, and Gautrey, 1998).

The current specification for short period response characteristics from the MIL-HDBK is given in Figure C-1. While $CAP = \frac{\omega_{sp}^{2}}{n/\alpha}$ has upper and lower boundaries, so does short period damping ratio.

In addition to the CAP and damping requirements given in the figure, for Category C Flight Phases (terminal operations), short period natural frequency and n/α shall be at least those given in Table C-1.

Next, for Level 3, the time-to-double amplitude, T_2, based on an unstable real root (if there is one) shall be not less than 6 seconds (compare to 55 seconds for an oscillatory phugoid). In addition, if there are any other Level 3 characteristics present, the minimum damping ratio of the short period shall be at least .05. Note that Level 3 does not insure safety.

Finally, this incarnation of requirements on short term response dynamics also includes a limitation on the equivalent time delay, τ_θ, as given in Table C-2 This time delay metric is generated by the Low Order Equivalent Systems matching process and is intended to account for any lags or delays associated with higher-order control system elements (not explicitly described by the fitted-to 4th order representation). These, too, have been debated, see for example, Field and Rossitto, (1999).

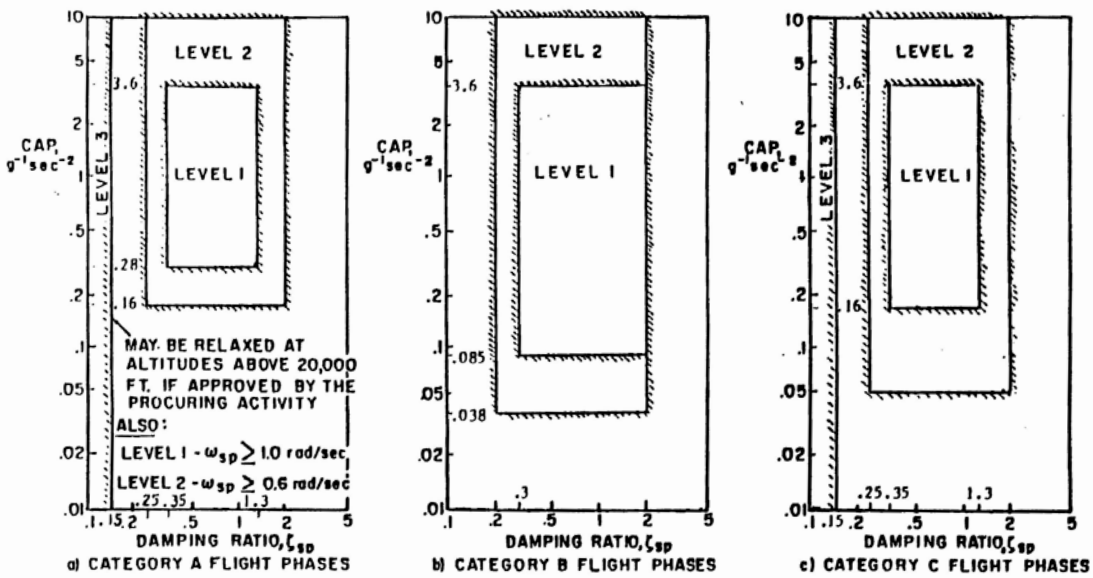


Figure C-1 Short Period Response Characteristics Requirements
(from US Department of Defense 1997)

Class	Level 1		Level 2	
	Min ω_{sp}	Min n/α	Min ω_{sp}	Min n/α
III (Large landplanes)	0.7	2.0	0.4	1.0

Table C-1. Additional Constraints on Frequency and n/α
(From US Department of Defense., 1997)

Level	Allowable Delay
1	0.1 sec
2	0.2 sec
3	0.25 sec

Table C-2. Allowable Equivalent Time Delay in Pitch
(From US Department of Defense., 1997)

Appendix D Requirements on Cockpit Feel Forces

Civilian Requirements on Control Forces

Both 14CFR25 and CS25 in Europe are harmonized on these points, and provide the following requirements. It is important to point out that the regulating authorities do not specify “feel system characteristics”. They only specify in very broad terms what the characteristics of the forces should be, including some guidance on what might be considered excessive forces and in a couple of cases, what is considered too light. Moreover, the regulations do not specify the source of the forces: the rules apply to mechanical systems, boosted systems, and fully fly-by-wire systems equally.

The primary quantitative reference to control forces is given in 25.143, for normal flying. The requirements list maximum forces to be considered limitations on pilot strength. These are given in Table D-1, and specify that the airplane should be in trim prior to executing the specified manoeuvre.

	Pitch	Roll	Yaw
Short –term 2-hands	75 lbs.	50 lbs.	
Short-term 1-hand	50 lbs.	25 lbs.	
Short –term			175 lbs.
Long-term	10 lbs.	5 lbs.	20 lbs.

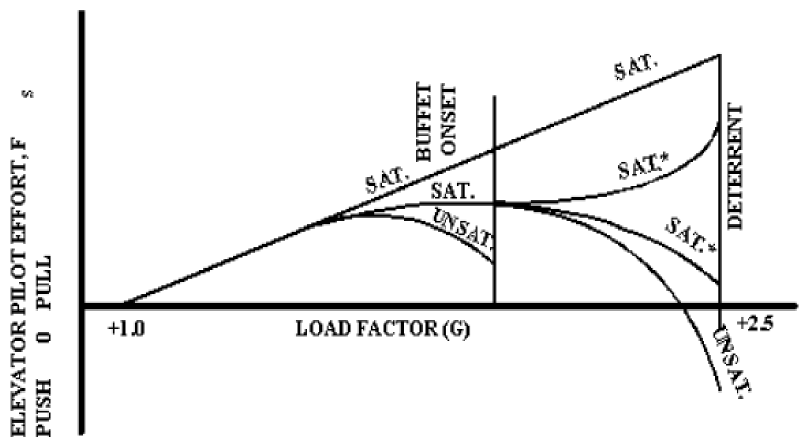
Table D-1. Civil Certification Pilot Force Limits.

Subparagraph (g) of 25.143 specifies that the longitudinal control force in manoeuvring lie within satisfactory limits: not so large as to require exceptional strength to manoeuvre; not so light as to require exceptional skill to avoid overcontrol and overstressing the airplane. The interpretive material in the Advisory Circular (FAA, 2012) suggests that a gradient of stick force per g of less than 120 pounds per g would meet the requirement of being “not excessive”, while a total force of more than 50 pounds to reach limit load would be acceptable as a minimum. (For Part 25 aircraft, flaps-up limit load is 2.5 g’s, or an increment of 1.5 g's above level flight. This suggests a minimum gradient of 33.33 lbs/g.) These are specified at high speed cruise conditions. While there is no numerical limit called out for other configurations, the qualitative requirement still applies.

Beyond these force limits, 25.173 prescribes the stick force per speed (static stability) to be not less than one pound in 6 knots. The static stability requirements also include a limitation on the "free return" speed, saying that when the control is released, the airplane should return to the trim condition which is within 10 % (7.5% for cruise), of the initial trim speed. This is effectively a limitation on the total system friction, although it's not stated as such.

Manoeuvring stick forces are regulated subtly by 25.251(e) which specifies the requirement for determination of a buffet envelope, but which also declares that "Probable inadvertent excursions beyond the boundaries of the buffet onset envelopes may not result in unsafe conditions."

Speeds Up to the Lesser of V_{FC} or M_{FC} or Buffet Onset at 1G



* These characteristics are satisfactory only in accordance with paragraphs 31b(5)(a)(1)(aa) and (bb).

Figure D-1. Part 25 Force Characteristics During Manoeuvring (From FAA(2012)

The definition of what constitutes an unsafe condition is given in the applicable means of compliance Advisory Circular, AC25-7C (2012). The longitudinal control force characteristics given there are reproduced in Figure 3-10, and specify that the stick force gradient against manoeuvre load factor may not reverse prior to initial buffet and the total stick force may not reverse at all prior to deterrent buffet.

There are similar requirements at speeds between V_{FC}/M_{FC} and V_{DF}/M_{DF} which are not repeated here.

High Speed Characteristics requirements of 25.253 refer to the ubiquitous “without exceptional strength…” and call for a push force at all speeds to V_{DF}/M_{DF} and no sudden or excessive reduction of elevator control force.

Paragraph 25.255 deals with characteristics at high speed in an out of trim condition. It specifies, in part, that from a specified mistrim condition, the slope of force vs load factor must be stable at all speeds up to V_{FC}/M_{FC} and the control force must not reverse at speeds up to V_{DF}/M_{DF}. In addition, from the out of trim condition at V_{DF}/M_{DF}, it must be possible to generate 1.5 g's with less than 125 pounds of force on the primary controller. Further, there are limitations on the local force gradient (e.g. it may not reverse prior to limit load or prior to V_{DF}/M_{DF}, and the total force vs. load factor may not reverse at all.

Elsewhere, the regulations are sprinkled liberally with the phrase "without requiring exceptional strength or skill", a meaningful but less than satisfying requirement which does not provide much in the way of detailed design guidance. One example of this aspect can be found in 25.253 above.

Military Requirements

For military airplanes in the US, the standard reference is MIL-HDBK-1797 which is a bit more specific regarding details of feel requirements because in addition to total forces, it also puts limits on breakout and friction. Total force limits are given in Table D-2; breakout force limits are given in Table D-3. Note that the ranges are large, and the Level 1 limits are the same as the Level2/3 limits.

But these are only maximum force levels, not "optimum" force levels, and there is not necessarily a guarantee that anywhere in the given range is "optimum".

	Pitch	Roll	Yaw
Takeoff and Landing	50 lb. Pull	25 lb	100 lbs.
Sideslips	10 lb. Pull 3 lb. Push	10 lbs.	100 lbs.
Failure Transients	20 lb. for 5 seconds.	10 lbs.	50 lbs.
Engine Out			180 lbs.

Table D-2. MIL-HDBK-1797 Control Force Limits (US Department of Defense., 1997)

	Pitch	Roll	Yaw
Breakout Forces	0.5 – 7 lbs.	0.5 – 6 lbs.	1 – 14 lbs.

Table D-3. MIL-HDBK-1797 Control Breakout Force Limits (US Department of Defense., 1997)

One important detail given by the MIL-HDBK that is not provided in the civilian requirements is a force/deflection gradient of 5 lb/inch in pitch and maximum displacements in roll (60 degrees for wheels (110 for completely mechanical systems)). It is noted, however that the authors suggest that this minimum is as low as it is because of strong objections from manufacturers, and that "the number seems to have originated more from a rule of thumb than from hard data”. (US Department of Defense.,1997, p. 332.)

Another admonition in the MIL-HDBK is that care should be taken not to let the pitch control displacements get too large:

> “When the short-period frequency is low, the pilots tend to overdrive the airplane with large pulse-like inputs to speed up the response. Therefore the pilots might not have disliked the control motion gradients as much if the short-period response had been faster.” (US Department of Defense, 1997, p. 332)

This characteristic of pilots was introduced in Section 3.3.2

Appendix E Analysis of Hess Linearity Index

Hess's Linearity Index

Hess, in his evaluation of different system characteristics for rudder pedal control (Hess, 2004) noted a difference in closed loop responses as a function of these nonlinear elements. In order to characterize the results he found, he suggested a "linearity index" as a figure of merit, or way of quickly classifying the linearity of a system. In (Hess, 2004), Hess suggests a non-dimensional linearity index, given by

$$LI = 1 - \frac{Area(DABD) + Area(DBCD)}{Area(DEBFD)} \qquad \text{(E.1)}$$

Where A, B, C, D, E, and F are defined in Figure E-1, adopted from Hess (2004). Defined in this way, the linearity index is geometrically a measure of the area of DEBFD taken up by the friction band, DABCD.

This idea has considerable merit and deserves additional evaluation.

Consider first the linear case, illustrated in Figure E-2. For this case, points A and D are coincident, as are points B and C. Thus, Area(DABCD) is zero. Clearly for this case, the numerator in the Linearity Index expression (1) is zero, and LI = 1.

For the case of non-zero friction and non-zero breakout force, Hess' geometric definition is appropriate for the condition where Friction = Breakout with Friction and Breakout having been defined in Figure 3-14. Under this constraint, the system just centres on the return-to-neutral side.

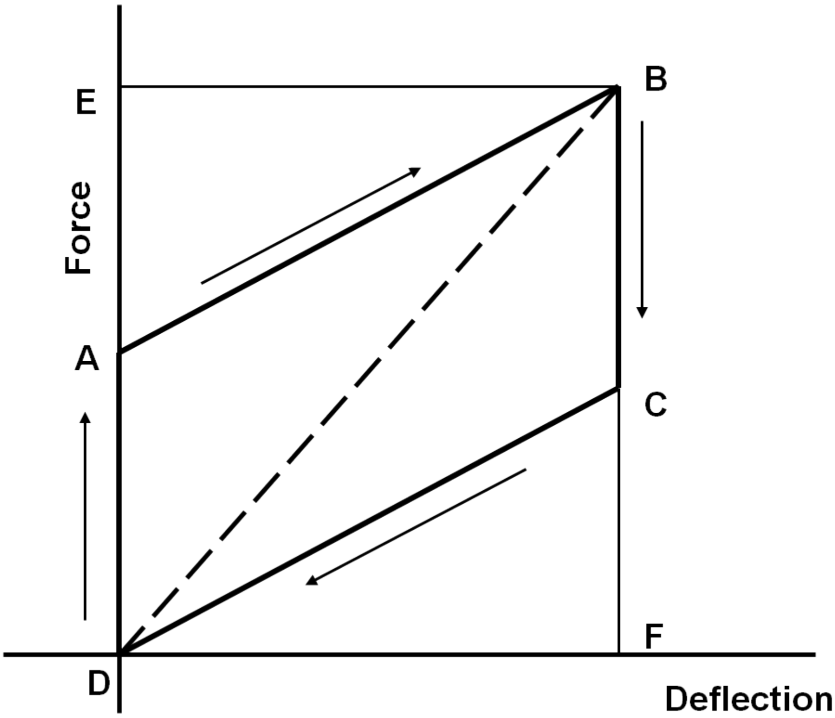


Figure E-1. Hess' Linearity Index Definitions.
(Adapted from Hess, 2004)

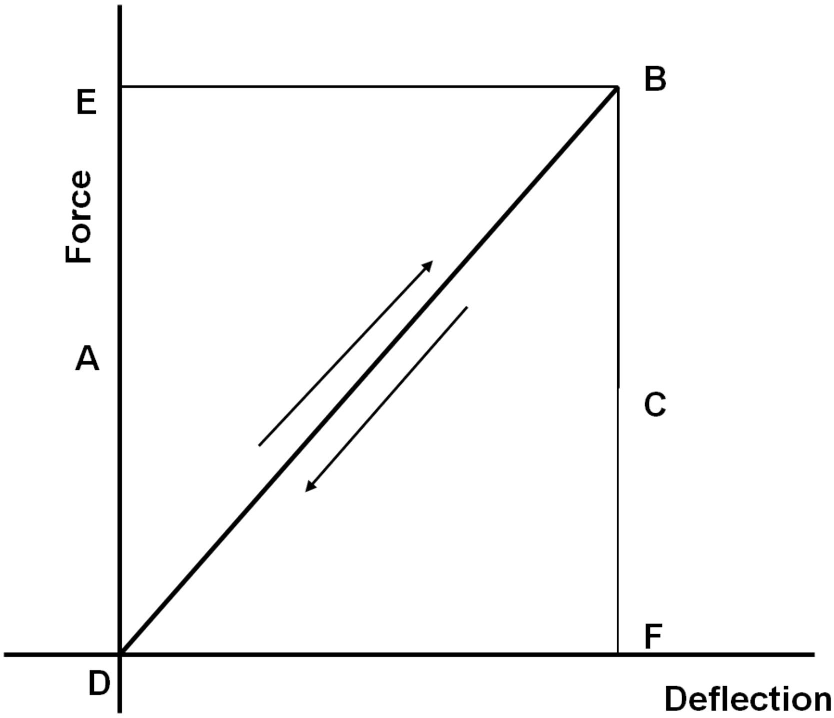


Figure E-2. The Case in which Friction = Breakout = 0.0.

Comparing Figure E-1 to Figure 3-14, it is clear that for Friction = Breakout, the force at point A is just twice the friction. For this geometry, the only command gradient available (the slope of AB) is given by

$$CommandGradient = \frac{Force(E) - Force(A)}{Deflection(F)} \qquad (E.2)$$

Since the Linearity Index is literally the proportion of the rectangle (DEBFD) taken up by the parallelogram (DABCD), it is convenient to set the force at E=1 and the deflection at F = 1. Recall from planar geometry that the area of a parallelogram as given in Figure E-3 can be expressed as

$$\text{Area} = \text{b} * \text{h} \qquad (E.3)$$

It is also important to note that the area is independent of the skew angle, α.

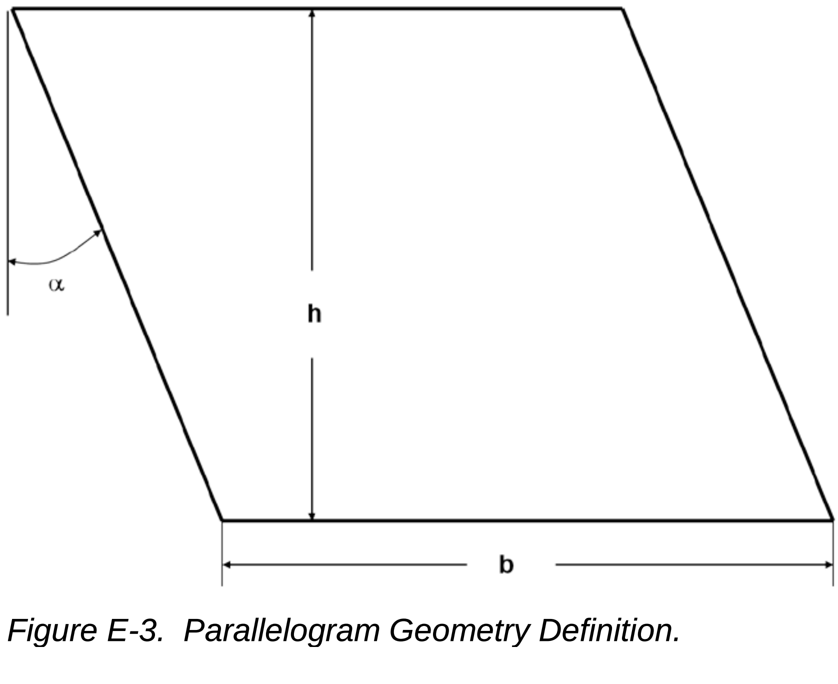


Figure E-3. Parallelogram Geometry Definition.

It is easy to show that the Linearity Index is a function only of the height of point A. With the force at point E (in figure E-1) defined as 1, the Linearity Index is then a function only of the percentage of the maximum force which is the force at point A, and since this is twice the friction, it is clear that

$$LI = 1 - 2Fr^* \tag{E.4}$$

where Fr* is the friction expressed as a fraction of the maximum force, Force(E).

This surprisingly simple result is a direct consequence of the geometric properties of the parallelogram.

It is useful to see what happens to LI as a function of the command gradient. That is, for a given value of friction (and breakout), allow the maximum force and maximum deflection to change. To do this, it is necessary to re-cast the expression for Linearity Index in terms of maximum force (Fm) and maximum deflection (instead of letting them be = 1.0). In terms of dimensional quantities, then, it can be shown that

$$LI = 1 - \frac{Area(DABD) + Area(DBCD)}{Area(DEBFD)} = 1 - \frac{2Fr}{Fm} \tag{E.5}$$

Consider first, the case of changing total force level. This is illustrated in Figure E-4 in which the total deflection is held constant but the total force (Length(DE)) is doubled to Length(DE'). As total force is changed for the same manipulator deflection, the command gradient gets steeper (and in fact closer to the "linear" gradient (slope(DB')), and LI increases. This is true because the lengths of the vertical parallelogram legs (Length(DA) and Length(BC)) are unchanged, and the maximum deflection (Length(DF)) is constant. The only geometric change to the parallelogram is the skew angle. Under these conditions, the area of the parallelogram is constant, but the total area of DE'B'FD increased by a factor of 2. In terms of equation (3.31), we see that the 2FR value (Length(DA)) became a much smaller percentage of the total force value (Length(DE')), and we would expect an increase in LI.

For example, for the shallower gradient (DABCD) in Figure E-1, let Length(DA)=.5Length(DE). Then LI = .5

For the steeper gradient, as Length(DE') is twice as long as Length(DE), but Length(DA) is the unchanged, and LI = .75.

This effect is recognized by Hess in (Hess, 2004).

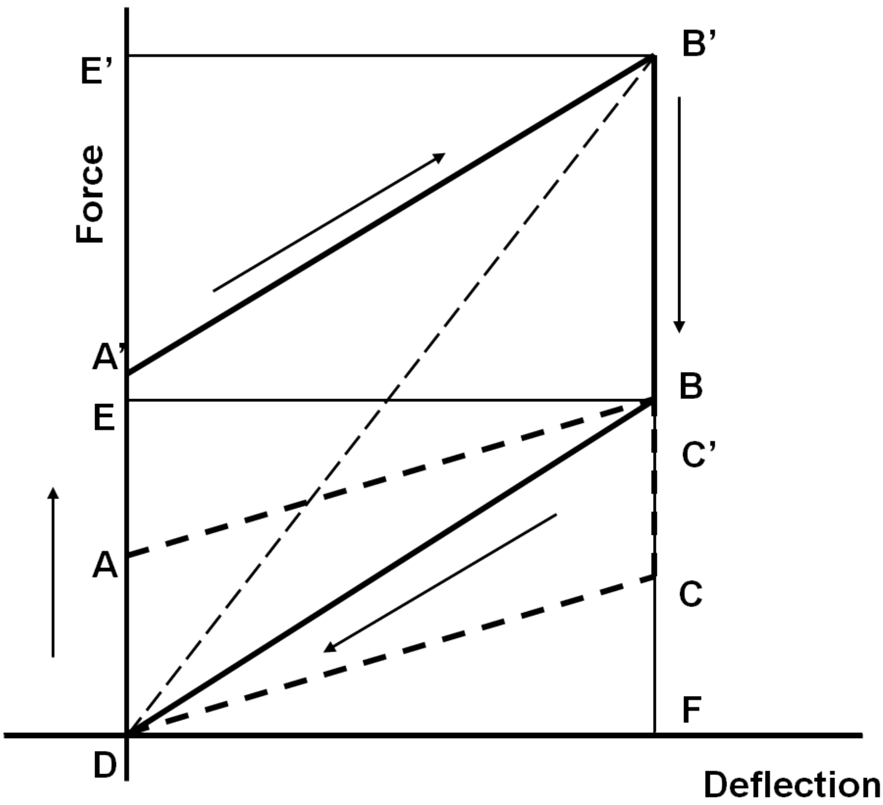


Figure E-4. Effect of Increasing Force Level

Second, consider doubling the manipulator travel at the same force levels, as in Figure E-5. In this case, as the displacement is increased, the command gradient decreases but LI does not change. This is because the area of the parallelogram Area(DAB'C'D) increases at the same rate as the total area(DEBFD). In fact, LI is a function only of the percentage of total force "used up" by twice the friction. Regardless of the fact that the command gradient (or manipulator force/displacement sensitivity) can be changed by changing the total deflection, the computed LI is invariant with the size of the deflection range.

To illustrate this point, consider the steeper gradient case of Figure E-5, and let Length(DE) = 2Length(DA). As in the analogous case from Figure E-4, then, LI = 0.5.

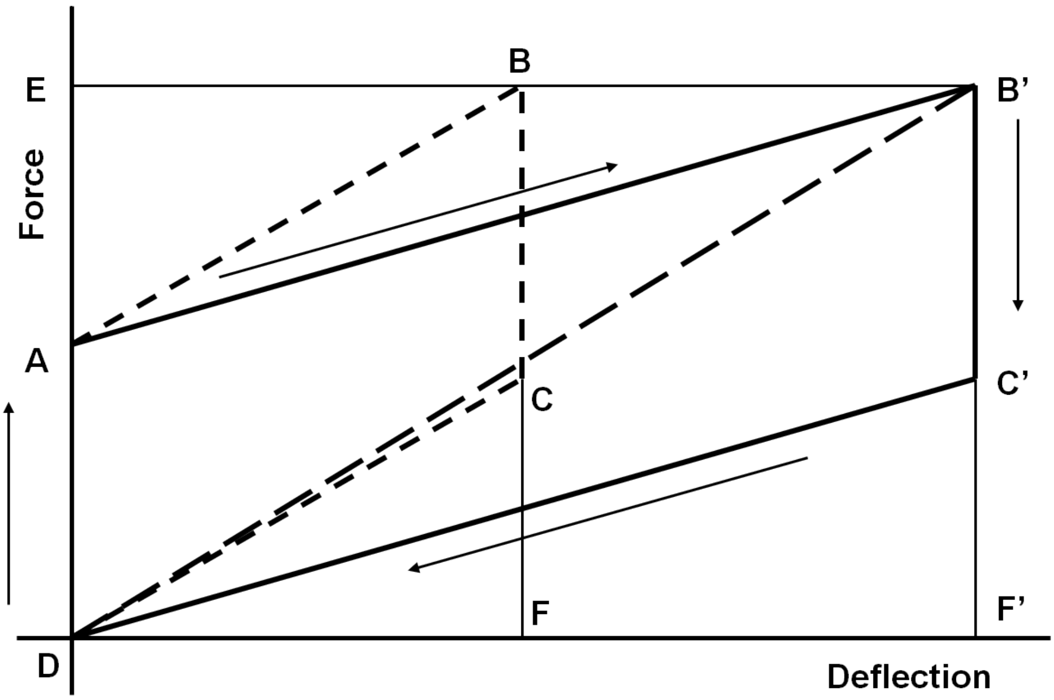


Figure E-5. Effect of Increasing Deflection.

Next, double the maximum deflection from F to F' while keeping the other parameters constant. In this case, from equation (E-5), LI = 0.5. This is true because equation (E-5) is not a function of total displacement.

What this points out is that this measure of linearity is just that: a measure of linearity. It is not necessarily a measure of sensitivity. Changing the command gradient via changing maximum forces gives a very different view compared to changing the gradient via changing the maximum deflection. While pilots are indeed sensitive to linearity, they are also sensitive to the command gradient itself (force/displacement "sensitivity"). These are related geometrically, but they are related in terms of pilot opinion in a much more complicated way (see, e.g. Lee, Rodchenko, Zaichik, (2004).

Nevertheless, this approach does capture some very important concepts. Small values of LI, as Hess points out are to be avoided. When he writes "A low LI value almost invariably indicates an overly sensitive force/feel system in which the breakout and maximum inceptor forces are not sufficiently separated in magnitude.", he is suggesting that the command gradient is too shallow. While a low value of LI can result from a shallow command gradient, it is not necessarily a predictor of it. What a low value of LI does capture, though, is gradient ambiguity (similarly undesirable) which is likely to show up as degraded pilot opinion, if not performance. This is a direct result of large friction (and required large breakout), and is a manifestation of the gradient ambiguity (between breakout and command gradients) noted earlier.

Appendix F Solution of Second Order Problem with Driving Function

Consider the second order differential equation

$$A\frac{d^2y}{dt^2}+B\frac{dy}{dt}+Cy=f(t), \qquad y\overset{\Delta}{=}y(t), \tag{F.1}$$

Then it can be shown that for $0 \le t$,

$$y(t)(=)\mathscr{L}^{-1}\left[Y(s)\right]=\mathscr{L}^{-1}\left[\frac{F(s)+y(0)(As+B)+y'(0)A}{As^2+Bs+C}\right] \tag{F.2}$$

Where $F(s)\overset{\Delta}{=}\mathscr{L}\left[f(t)\right]$, and y(0) and $y'(0)$ are the initial values of y and its first derivative.

Consider the driving function

$$f(t)=F_m\cos(\omega_1 t+\psi) \tag{F.3}$$

Where F_m, ω_1 and ψ are real constants.

Then

$$F(s)=\mathbf{L}\left[F_m\cos(\omega_1 t+\psi)\right]=\frac{gs+h\omega_1}{s^2+\omega_1^2} \tag{F.4}$$

Where $g \stackrel{\Delta}{=} F_m \cos\psi$, and $h \stackrel{\Delta}{=} -F_m \sin\psi$

Then

$$Y(s) = \frac{gs + h\omega_1 + [y(0)(As + B) + y'(0)A](s^2 + \omega_1^{\,2})}{(s^2 + \omega_1^{\,2})(As^2 + Bs + C)} \qquad \text{(F.5)}$$

The factor $(s^2 + \omega_1^{\,2})$ has its origins in the driving function. The zeros of this factor are denoted $s_1, s_2 \stackrel{\Delta}{=} \pm j\omega_1$

The other denominator factor comes from the LHS of the original differential equation. This is the characteristic equation of the system formed by setting this factor to zero.

$$As^2 + Bs + C = 0 \qquad \text{(F.6)}$$

The roots of this equation will be denoted $s_3, s_4 \stackrel{\Delta}{=} -\alpha \pm j\beta$

Where

$$\alpha \stackrel{\Delta}{=} \frac{B}{2A}, \qquad \beta \stackrel{\Delta}{=} \sqrt{\beta_0^2 - \alpha^2}, \qquad \beta_0^2 \stackrel{\Delta}{=} \frac{C}{A}. \qquad \text{(F.7)}$$

Gardner and Barnes point out that the form taken by the final result depends on the numerical value of β^2. This example assumes that $\alpha^2 < \beta_0^2$ so that β^2 is positive and the final result will be a damped oscillation.

The roots of the characteristic equation (F.6) are called the characteristic values:

- α is called the damping constant
- β is called the characteristic angular frequency
- β_0 is called the undamped angular frequency, the limiting value of β as the damping approaches zero.

Substituting into the expression for Y(s),

$$Y(s) = \frac{gs + h\omega_1 + [y(0)(As + B) + y'(0)A](s^2 + \omega_1^2)}{A(s^2 + \omega_1^2)[(s+\alpha)^2 + \beta^2]} \tag{F.8}$$

It can be shown that the final result in the time domain can be written as

$$\begin{aligned} y(t) &= \frac{F_m}{A[(\beta_0^2 - \omega_1^2)^2 + 4\alpha^2\omega_1^2]^{1/2}} \cos(\omega_1 t + \psi - \theta) \\ &+ \frac{1}{A\beta}\left[\frac{m^2 + n^2}{(\beta_0^2 - \omega_1^2)^2 + 4\alpha^2\omega_1^2}\right]^{1/2} e^{-\alpha t}\cos(\beta t + \lambda) \end{aligned} \tag{F.9}$$

For $0 \le t$, in which

- $\theta \overset{\Delta}{=} \tan^{-1}\dfrac{2\alpha\omega_1}{\beta_0^2 - \omega_1^2}$
- $m \overset{\Delta}{=} \beta[g + y(0)A(\omega_1^2 - \beta_0^2) - y'(0)B]$
- $n \overset{\Delta}{=} h\omega_1 - g\alpha + y(0)\alpha A(\omega_1^2 + \beta_0^2) + y'(0)A(\alpha^2 + \omega_1^2 - \beta^2)$, and
- $\lambda \overset{\Delta}{=} \tan^{-1}\dfrac{-n}{m} - \tan^{-1}\dfrac{-2\alpha\beta}{\alpha^2 + \omega_1^2 - \beta^2}$

Now the first term in (F.9) is the steady-state portion of the response, having the same sinusoidal waveform and the same frequency as the driving function. The second term in (F.9) is the transient portion of the response. It has its origins in the solution of the system characteristic equation. The damping constant α is given by the magnitude of the real portion of the poles. The time constant is the reciprocal of the damping constant. The characteristic angular frequency β is the magnitude of the imaginary part of the poles. Gardner and Barnes (1942) point out that both α and β depend "*solely* on the constants of the physical system and the system's interconnection, and are *independent of its excitation*". (p. 173) (emphasis added)

While the *character* of the transient is determined by the locations of the system poles, the *amplitude* is determined by the initial conditions and the initial phase of the driving function. This can be seen in the parameters m and n. It is clear that selection of these conditions can generate a transient term of appreciable size compared with the steady-state solution. Moreover, since the frequencies of the two terms which make up the total solution are different, the total solution may appear chaotic. Gardner and Barnes point out that even with zero initial conditions, there will always be a transient evident in the total solution, since there is no value of ψ which makes both m and n zero.

Appendix G Application of Dynamic Oversteer

The contents of this Appendix are held by the author.

Dynamic Oversteer and all associated technologies are protected by patent*.

* See Hiltner and Lee, (2007)