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College of Aeronautics Report No 9305
April 1993

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REPORT ON A VISIT TO THE ARVIN/CALSPAN CORPORATION BUFFALO, NEW YORK, USA SEPTEMBER 1992

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"The views expressed herein are those of the author alone and do not necessarily represent those of the Institute"

ACKNOWLEDGEMENTS

This report is a summary of a visit made to the Arvin/Calspan Corporation in Buffalo, New York, USA, by Mr. Edmund Field in September 1992.

The visit was made in support of a Total Technology PhD research programme, performed within the Flight Dynamics Group of the College of Aeronautics, under the supervision of Mr. Michael Cook. The Industrial collaboration for the programme is with British Aerospace Regional Aircraft, Woodford, with Mr. David Gregory providing the industrial supervision.

The visit was funded by the first prize of the Coachmakers Award, a scheme to allow College of Aeronautics students to visit foreign organisations in support of their studies, funded by the Worshipful Company of Coachmakers and Coach Harness Makers under the Eric Beverley Memorial Trust. The flight in the variable stability Learjet was funded by the College of Aeronautics.

Contact with the Arvin/Calspan Corporation was made during their Seminar Course on Augmented Aircraft Handling Qualities given in June 1992 to the test pilot and flight test engineer students of the International Test Pilot School (ITPS), Cranfield, which the author attended with the kind permission of ITPS. The course was given by Calspan engineering test pilots Michael Parrag and Paul Deppe, who subsequently provided the contact at Calspan, and whose help in organising the visit was invaluable.

Finally the assistance of Mr. Roger Bailey, College of Aeronautics Chief Test Pilot, during the preparation of this report is greatly appreciated.

This report is an edited version of the internal CoA Report No. NFP 9202, issued in November 1992.

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Abbreviations

AFTI	Advanced Fighter Technology Integration
AGL	Above Ground Level
ASTTA	Avionics Systems Test and Training Aircraft
ATC	Advanced Technology Centre
ATF	Advanced Tactical Fighter
BAC	British Aircraft Corporation
CAL	Cornell Aeronautical Laboratories
CFPD	Command Flight Path Display
CoA	College of Aeronautics
DAC	Douglas Aircraft Company
EPNER	Ecole du Personnel Navigant d'Essais et de Reception
FAA	Federal Aviation Administration
FBW	Fly By Wire
FCS	Flight Control System
GMT	Greenwich Mean Time
HDD	Head Down Display
HOS	Higher Order System
HSCT	High Speed Civil Transport
HUD	Head Up Display
IFR	Instrument Flight Rules
IFS	In-Flight Simulator
ILS	Instrument Landing System
IPP	Integral Plus Proportional
ITPS	International Test Pilot School
LAHOS	Landing Approach High Order Systems
NLR	National Aerospace Laboratory, the Netherlands
NASA	National Aeronautics and Space Administration
PIO	Pilot Induced Oscillation
PR	Pilot Rating
PVD	Peripheral Vision Display
QNH	Local altimeter setting to give altitude above mean sea level
SCAS	Stability and Control Augmentation System
SCR	Supersonic Cruise Research (aircraft)
SPPO	Short Period Pitching Oscillation
SST	SuperSonic Transport
TIFS	Total In-Flight Simulator
USAF	United States Air Force
VFR	Visual Flight Rules
VHS	Video Helical Scan
VISTA	Variable In-flight Simulator Test Aircraft
VSS	Variable Stability System
VTOL	Vertical Take Off and Landing

NOTATION

Symbols

F_s/n_z	Stick force gradient
P_E	Period of equivalent second order response
T_2	Time to double bank angle
a_{LF}	Delay time
dB	Decibels
g	Acceleration due to gravity
h	Height
lb	Pound weight
msec	Milli second
n_z	Normal acceleration
q	Pitch rate
q_c	Commanded pitch rate
rms	Root mean square
$1/T_{h1}$	Lower frequency zero in h/δ_e transfer function
α	Angle of attack
δ_e	Elevator deflection
θ	Pitch attitude
$1/T_{\theta 1}$	Lower frequency zero in q/δ_e transfer function
$1/T_{\theta 2}$	Higher frequency zero in q/δ_e transfer function
ω	Natural frequency
ω_{sp}	Short period natural frequency
ζ_p	Phugoid damping ratio
ζ_{sp}	Short period damping ratio

1. INTRODUCTION

The visit to the Arvin Calspan Corporation in Buffalo was made in support of a PhD programme undertaken in the College of Aeronautics (CoA). The research topic concerns flying and handling qualities of advanced fly-by-wire civil aircraft.

With the introduction of electronic Flight Control Systems (FCS) the responses of aircraft to a pilot input can become highly modified compared with that of conventional aircraft. As such systems have been introduced to military aircraft problems associated with their flying and handling qualities have become apparent. Much research and development work has been undertaken into understanding and solving these problems and producing military aircraft that handle well. Although this work continues, today's aircraft demonstrate a vast improvement on earlier designs.

While much research has been undertaken into the flying and handling qualities of military aircraft considerably less has been performed in the area of civil aircraft. Consequently there are few guidelines for the design, assessment and certification of the civil aircraft now being produced that utilise electronic FCS.

The purpose of this PhD programme is to address the deficiencies in the civil aircraft field and apply the knowledge and technologies of the military designs and criteria where applicable. In order to do this it is necessary to obtain a thorough understanding of the work undertaken in both the military and civil fields, and to gain exposure to problems that have been identified.

The Arvin/Calspan Corporation has been involved in handling qualities research since the 1940's and through it's numerous research programmes utilising it's variable stability aircraft has become recognised as one of the world leaders in the field of handling qualities.

Therefore a visit to the headquarters of the Flight Research Department of the Arvin/Calspan Corporation in Buffalo was made in support of this study. The two main purposes were to undertake a literature search of their reports from their research programmes of relevance to this study and to perform an engineering test flight in one of their two Variable Stability Learjet In-Flight Simulators, to demonstrate features of modern FCS designs.

During the visit the opportunity was also taken to discuss the more recent developments in the field with Calspan personnel. In addition contact was made with the Stability, Control, Simulation and Flying Qualities Technology Group of the McDonnell Douglas Corporation, Long Beach, who were conducting a TIFS investigation during the visit.

2. ARVIN/CALSPAN CORP, FLIGHT RESEARCH DEPARTMENT

The Calspan Advanced Technology Centre (ATC), located near Buffalo, New York, dates back to 1946, then known as the Cornell Aeronautical Laboratories (CAL), when its principle facilities were a subsonic wind tunnel, flight research hangar and a machine shop. Today the ATC is one of three divisions of the Calspan Corporation which has grown into one of America's largest independent research organisations.

The Calspan Corporation was bought by Arvin Industries Inc. of Columbus, Indiana, in the early 1970's. Arvin is a global company engaged in automotive original equipment and replacement parts, industrial products, and research/development services. Its interests are not closely linked to those of the Calspan Corporation which operates independently, the Flight Research Department being an entity in its own right. The structure of the organisation is given in figure 1.

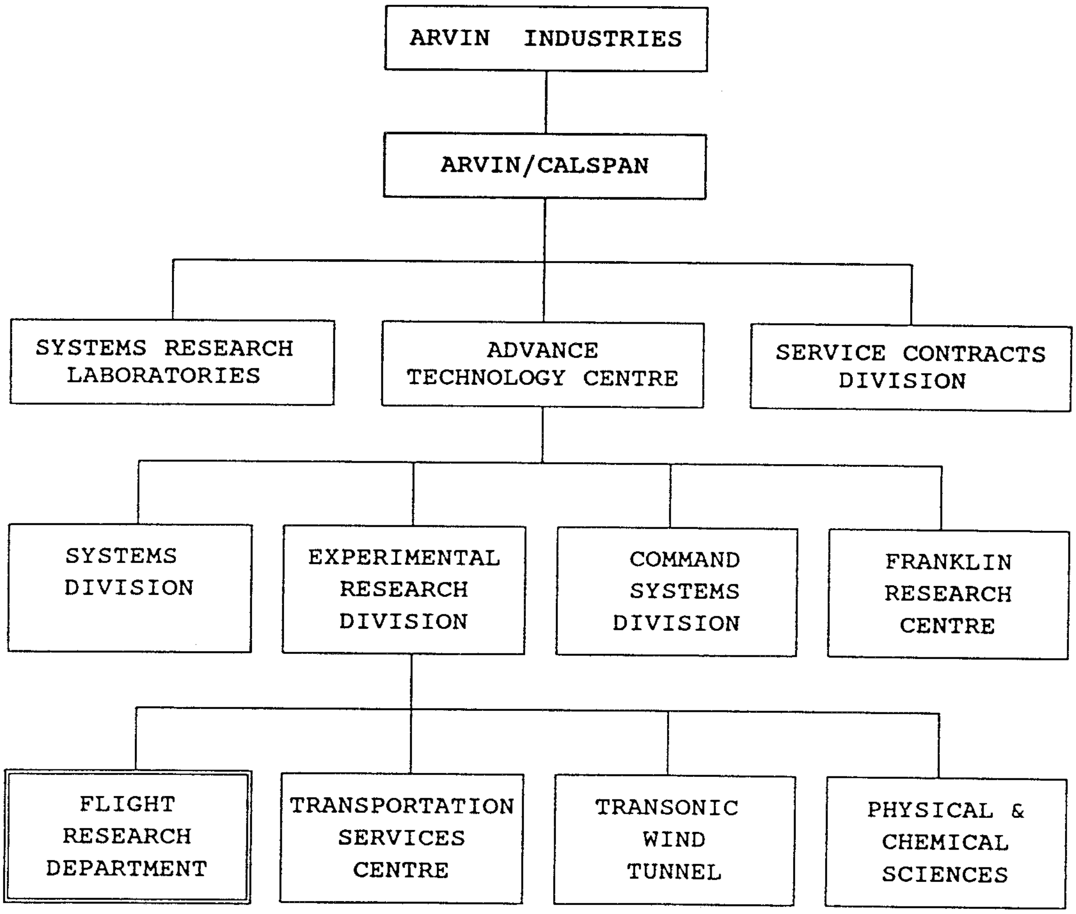
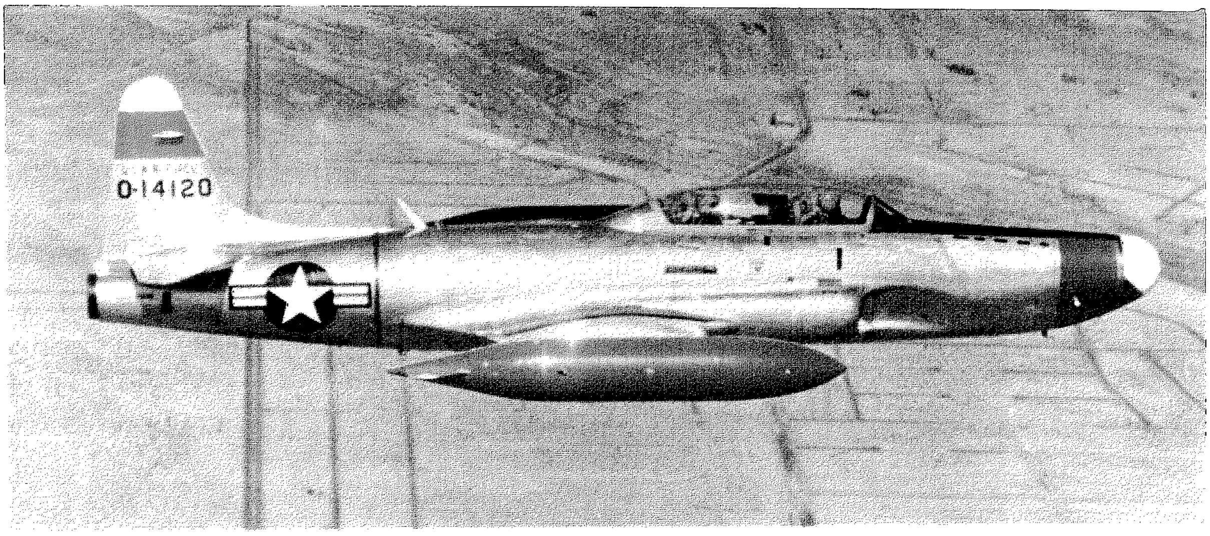


Figure 1. ARVIN/CALSPAN Organisational Structure

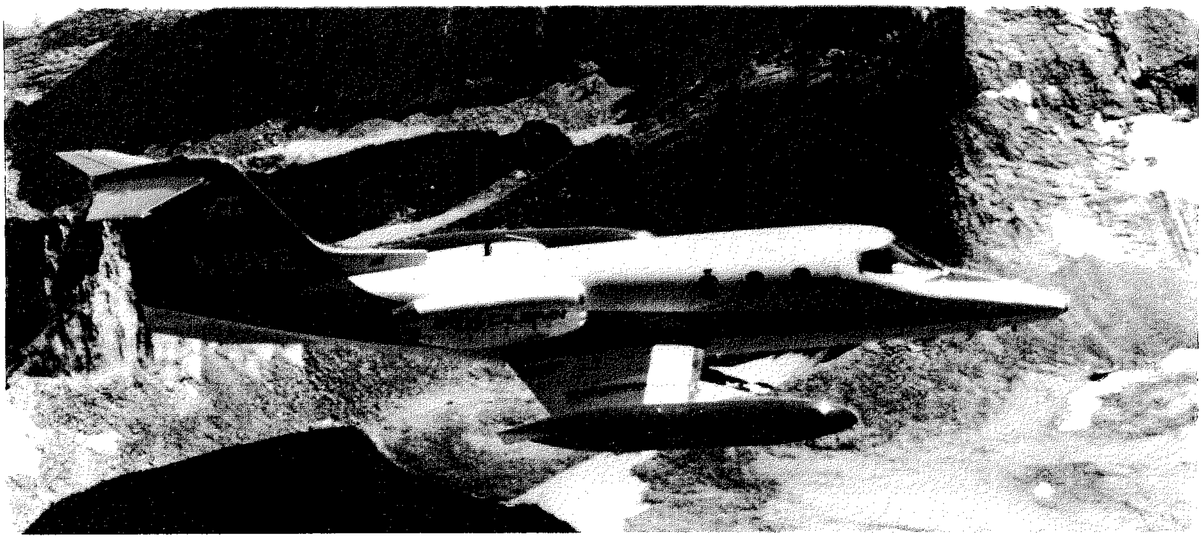
The Arvin/Calspan Flight Research Department (hereafter referred to as Calspan) has been at the forefront of development and operation of variable stability aircraft since 1948, pioneering in-flight simulation technology. These aircraft have been used for research into flight control systems, flying and handling qualities, cockpit displays and controllers, avionics integration, man-machine interfaces and the interactions between these factors and other airplane subsystems. The aircraft are also used for test pilot and flight test engineer training at various test pilot schools.

Currently Calspan operate four variable stability in-flight simulator aircraft, the NT-33A, NC-131H Total In-Flight Simulator (TIFS) and two Learjets, figure 2. In addition they also operate the variable stability US Navy VTOL X-22A, although this has not flown for several years, and a Piper Aztec instrumented for meteorological and environmental research.



a) USAF/CALSPAN NT-33A

b) USAF/CALSPAN Total In-Flight Simulator (TIFS)



c) CALSPAN Lear 24F

Figure 2. CALSPAN Variable Stability Aircraft

3. VARIABLE STABILITY AIRCRAFT

Variable stability aircraft are used for two primary roles. Firstly for training test pilots and flight test engineers and secondly for research and development in the areas of aircraft dynamics, stability, control and handling.

During test pilot and flight test engineer courses students are exposed to a wide variety of aircraft chosen to exhibit different stability and control properties. During the Stability, Control and Handling part of the course it is desirable for the students to obtain experience in aircraft that cover a wide cross section of handling characteristics. However the aircraft flown are mostly production aircraft, with some minor modifications where appropriate, and so should all have acceptable handling performance. Therefore the pilots will not be exposed to undesirable characteristics or learn how to expose and recognise these.

The benefit of a Variable Stability aircraft is that with one airframe the stability of the aircraft may be altered in flight so that the student can gain experience of many different characteristics, both good and bad, and so may become aware of desirable and undesirable features, and also become aware of the appropriate test techniques to assess an aircraft for these features in the future. Furthermore this can all be done within the safe environment of the baseline stable and well behaved aircraft.

Demonstration flights of this kind, in Calspan developed and operated variable stability B-26s, became an integral part of the US Air Force and Navy courses in the early 1960's. The Cranfield modified Beagle Basset has been used at the Empire Test Pilots School, Boscombe Down since the early 1970's. By today's standards these aircraft are fairly basic. The tutor can alter the aerodynamic derivatives of the aircraft through simple dials. With these changes the response of the aircraft changes. However these changes are limited and one alteration may produce several effects. For example in order to change the short period natural frequency, the damping may also change. Therefore in order to obtain the required total dynamics it may be necessary to augment several aerodynamic properties. In addition to changes to the aerodynamic derivatives time delays and effects of simple lead/lag filters can be demonstrated.

A development from variable stability aircraft has been the In-Flight Simulator, as pioneered by Calspan. With the more complex system and increased computer power it is now possible to specify the exact response of the aircraft being modelled. From the tutor's point of view he can now isolate one particular feature, for example short period damping, and with minimum effort alter this parameter by a few simple keystrokes, without altering other characteristics, such as the natural frequency, at the same time.

The other main use of variable stability aircraft has been for research and development. In terms of pure research it is possible to change certain parameters and have pilots assess the different configurations to determine which are best and which worst. For instance acceptable and desirable boundaries for the short period natural frequency and damping may be investigated in this manner.

While many of the principles demonstrated in variable stability aircraft can also be demonstrated in ground simulators, the in-flight simulator provides a realism not possible with the ground system. It provides complete motion and visual reproduction, the actual cockpit environment and the true psychological flight environment. Whereas ground based simulators have been used with some success to expose problems with a FCS design before flight test, this is primarily in the longitudinal axis. Ground based simulators are unable to provide the necessary lateral accelerations which expose problems in these modes, as witnessed by problems with the F-16, F-18 and Saab Gripen.

These problems can be exposed with in-flight simulators as they can be safely used to accurately perform realistic high gain closed-loop control tasks to investigate the performance of even the most controversial control system designs. Furthermore all of Calspan's aircraft can be used with the variable stability system engaged even during landings.

Details of the four In-Flight simulators currently operated by Calspan follow.

3.1 USAF NT-33A

The variable stability Lockheed NT-33A has been employed since 1958 on a variety of flying qualities research programmes and aircraft simulations. It has a fully programmable Head-Up Display and associated sensors to examine the interaction of display characteristics and flying qualities. Test pilot students fly the NT-33A to evaluate the side stick controller and Head-Up Display.

The following three sections describing the Lockheed NT-33A are reproduced from the Calspan aircraft description brochure.

NT-33A Description

The USAF/Flight Dynamics Laboratory's NT-33A is a unique research aircraft capable of simulating the flight characteristics of a wide range of other aircraft. It has been an instrumental tool in the development of new fighter aircraft and for the investigation of aircraft handling qualities over thirty years.

The NT-33A, modified and operated by Calspan Corporation under USAF contract as an in-flight simulator, is an extensively modified Lockheed T-33 trainer. The original T-33 nose section has been replaced by an F-94 nose, providing space for the recording equipment and the electronic components of the variable stability flight control system.

The front seat controls have been replaced by a full-authority fly-by-wire flight control system and a variable response, artificial feel system. The evaluation pilot, who sits in the front cockpit, controls the aircraft through a centre or sidestick controller, and a rudder pedal arrangement, figure 3. Other cockpit controllers can be installed in the NT-33A to replicate specific aircraft configurations.

The rear cockpit contains the original mechanical flight control system of the T-33. The safety pilot who occupies the rear cockpit can immediately assume control of the aircraft if a problem develops with control of the simulated aircraft that is being flown by the front seat pilot. The safety pilot also serves as the systems operator by setting up the research experiments, aircraft configurations, and HUD formats.

A programmable analog and digital flight control system allows the airplane to simulate the flying qualities of many existing aircraft, future aircraft, and hypothetical configurations. The inherent versatility of the variable stability system (VSS) is ideal for systematic in-flight evaluation of variations in flight control and aircraft dynamics. Additionally, the Display Evaluation Flight Test system and associated ground-based software support facility provide a fully programmable Head-Up Display (HUD) that complements the variable stability features of the airplane for cockpit display research and evaluation.

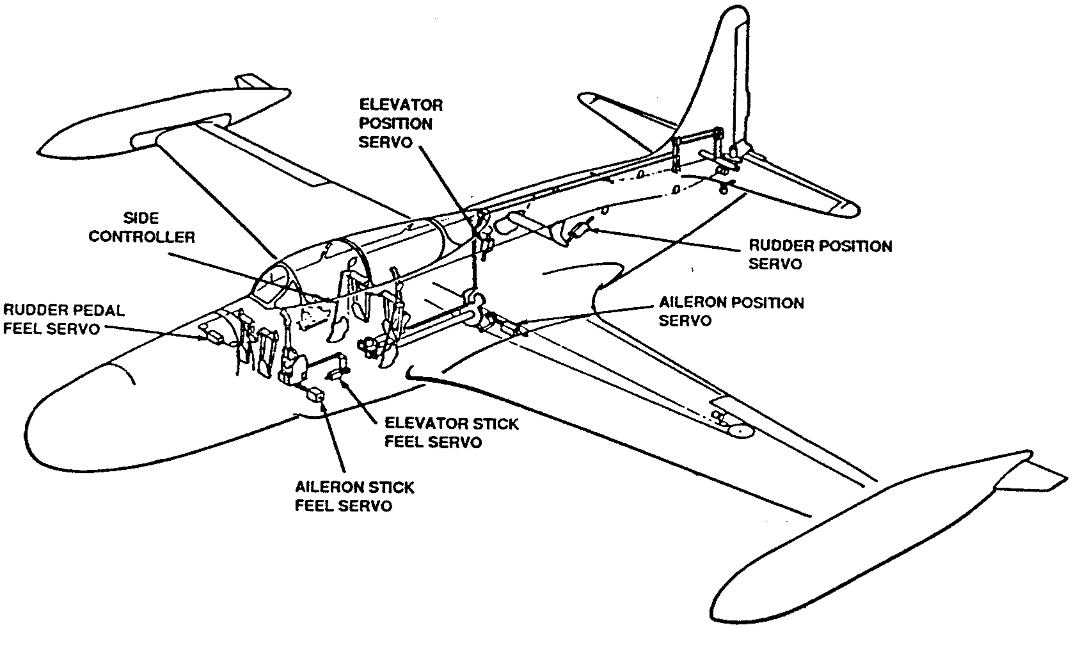


Figure 3. NT-33A Control System Layout

Simulation Method

The NT-33A makes use of response feedback methodology illustrated in figure 4. The NT-33A's stability and control characteristics are augmented through use of appropriate feed-forward and feedback VSS gains. The inner loops of the variable stability system provide the desired dynamics for the unaugmented simulated airframe.

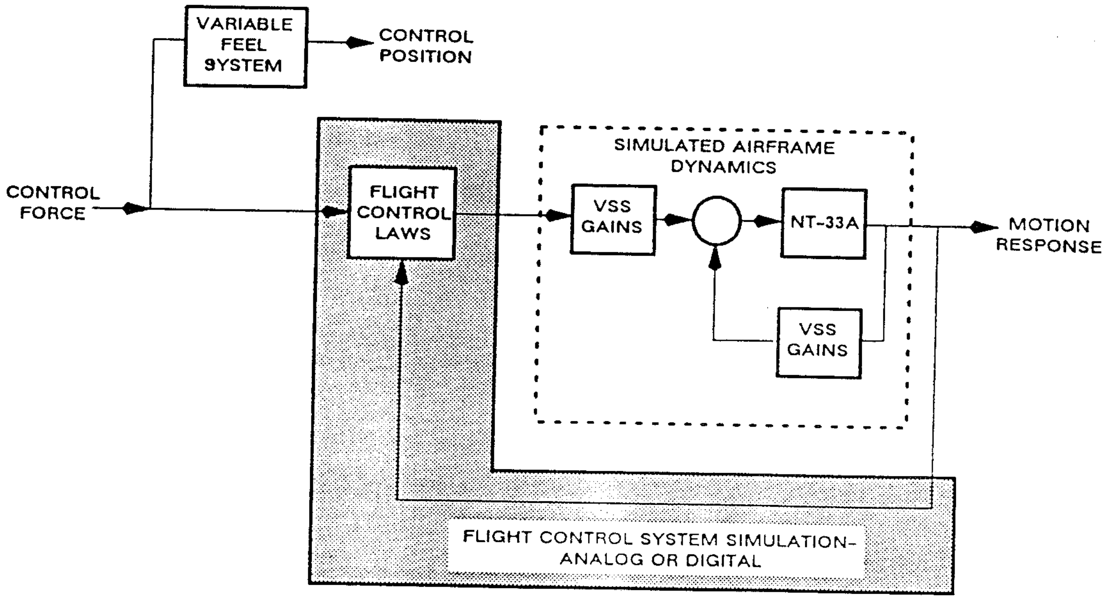


Figure 4. Basic Airframe and Flight Control Simulation Used by the NT-33A

The simulation is achieved by the appropriate deflection of the NT-33A elevator, aileron and rudder control surfaces commanded by the analog fly-by-wire system. The fly by wire system receives electrical inputs from the front cockpit pilot's controls, alpha vane, beta probe, rate gyros and accelerometers. The effects of these inputs are varied by the adjustment of potentiometers in the rear cockpit.

Around the simulation of the unaugmented airplane, analog or digital flight control laws can be implemented. These control laws can be programmed exactly as they are in an aircraft prototype. During an in-flight simulation project the control laws of the simulated aircraft may easily be modified to improve the handling qualities of the design.

Cockpit control feel is provided to the evaluation pilot by a variable electo-hydraulic feel system operating on the centre stick and on the rudder pedals. Variations in feel system characteristics, such as breakout, hysteresis, and force-position gradients, as well as the dynamic response parameters of damping and frequency, can be simulated.

No-motion ground simulation can also be provided by using the NT-33A as a simulator cab. Instead of the aircraft motion sensors, NT-33A dynamics are generated on the ground by a PDP-1144 digital computer. The VSS, flight control system, and cockpit controllers are used the same whether on the ground or in-flight.

Programmable Head-Up Display

The Kaiser AVQ-7 Head-Up Display in the front cockpit is optically identical to the unit installed in A-7D/E aircraft. The symbology is generated by a Kaiser F-18 Multi-Function Display Indicator (MDI) with the symbol dynamics and display computations performed in the same Rolm 1602 multiple purpose computer used to program the digital flight control laws. This system allows easy reprogramming of the display content and dynamics, including a wide variety of displays that can be selected in-flight. The HUD and front cockpit external views are continually recorded on a VHS format video cassette. A video display in the rear cockpit allows the safety pilot to monitor the HUD and provides him with a forward field of view.

A mode control unit in the rear cockpit allows push button mode control and data insertion. Two front cockpit declutter switches allow front cockpit mode/format control.

A vision-restricting device, employing a blue helmet visor and translucent amber windscreen panels, simulates instrument/night conditions. With the blue visor up, the pilot can see outside through the amber windscreen. With the blue visor down, outside vision is obscured, but the HUD and instrument panel remain visible.

NT-33A Simulation Programmes

The NT-33A has been used in many flying qualities research programmes covering the areas of flight control design and display characteristics. Many of these are covered in the literature reviews given in the appendix.

In addition the aircraft has been used to evaluate the flying qualities of several aircraft prior to first flight, and to fine tune problems with FCS designs uncovered either during development or flight test.

Aircraft programmes with which the NT-33A has been involved include the North American X-15, Fairchild A-10 Thunderbolt, McDonnell Douglas F-15 Eagle, Northrop YF-17, General Dynamics F-16 Fighting Falcon, McDonnell Douglas F-18 Hornet, AFTI/F-16, Israeli Aircraft Industries LAVI, Saab JAS-39 Gripen (post landing accident modifications to the FCS), VISTA/NF-16 and the successful ATF competitor, the Lockheed/General Dynamics/Boeing YF-22A.

3.2 USAF NC-131H TIFS

History (reproduced from Calspan aircraft description brochure)

Calspan has developed a number of variable-stability aircraft dating back to early 1950's. TIFS, which was developed in the late 1960's under Air Force Flight Dynamics Laboratory sponsorship, is the most advanced version of these aircraft. The Air Force objectives were to advance simulation technology for flying qualities research and to help develop new Air Force airplanes. The FAA, interested in simulating SST landing visibility, also helped initiate the project. The Air Force furnished a C-131B as the basic airframe, supplemented by a separate cockpit, side-force surfaces, direct lift flaps, computer controlled hydraulic actuators, and turbo-prop engines. The final aircraft, designated an NC-131H, first flew in July 1970, figure 5. In 1985, an avionics nose, which is interchangeable with the simulation cockpit, was developed. This systems test configuration of TIFS is called the Avionics Systems Test and Training Aircraft (ASTTA). It hosts radar, infrared, and electo-optical detection systems as well as inertial navigation and a Global Positioning System. It is a highly instrumented flying test bed used to test tactical sensors and other avionics systems. It is also a unique tool to train systems designers, evaluators, and users in airborne test techniques with a crew station installed in the aft cabin.

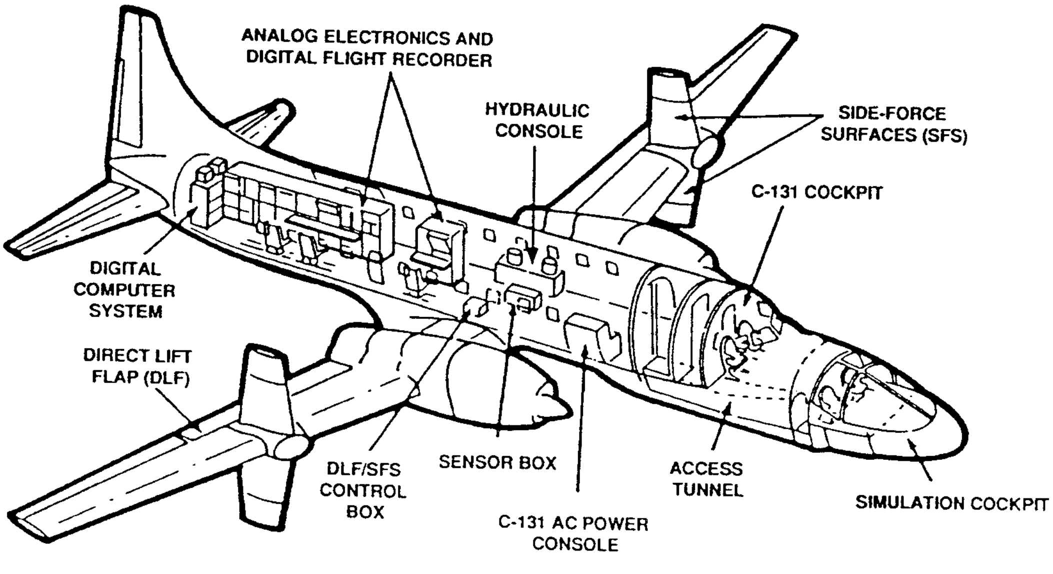


Figure 5. TIFS Simulation Configuration

Major Features

Whereas Calspan's other in-flight simulators can produce variable dynamics around the three rotational axes, TIFS has control over all six rigid body degrees of freedom, and so is able to match all rotational and translational responses, of the complete aerodynamic and control system model, at the pilot station. It is therefore able to reproduce the complete motion and visual environment of even the most advanced aircraft concepts. An accurate model following control system, figure 6, which utilises the elevator, ailerons, rudder, throttle, direct lift flaps and side force surfaces driven by purpose built high bandwidth actuators, ensure that TIFS produces motions that accurately duplicate the computed response of the simulated aircraft. The simulation is also achieved by the visual cues that are produced by the actual flight environment with all its subtle effects. In addition turbulence, cross winds and windshear effects can be modelled.

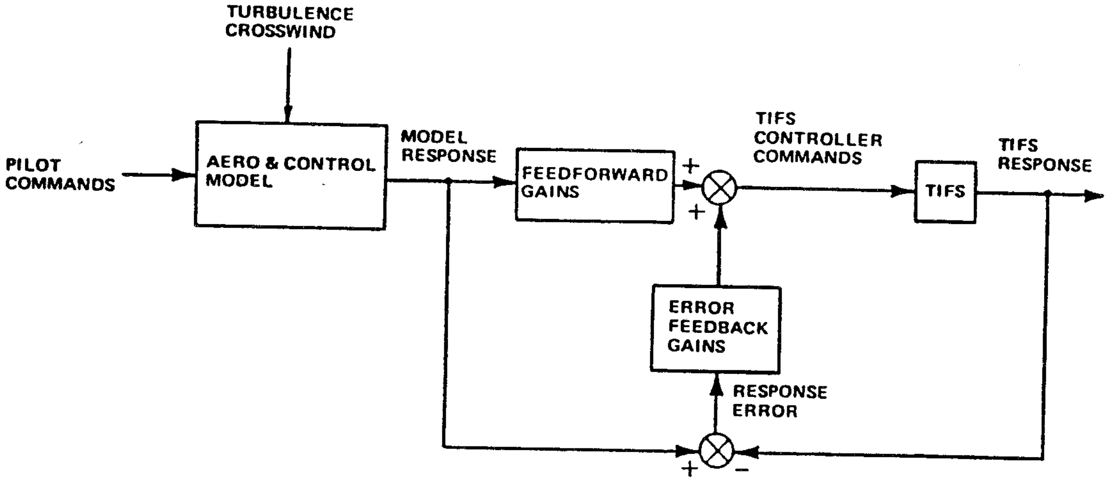


Figure 6. TIFS Model Following Simulation

TIFS is unique in that it has two separate cockpits. The evaluation pilot sits in a separate cockpit attached to the front of the aircraft, which is readily accessible for in-flight crew changes, while the safety pilots sit at the controls of the near original C131-B cockpit behind and above the simulation cockpit. The workload for just one safety pilot can be excessive during critical simulations, especially landing approaches, therefore TIFS uses two safety pilots. The advantage for the evaluation pilot of this arrangement is that he has a wide field of view, which can be screened to represent that of the simulated aircraft, in a large cockpit that can be customised with an array of different displays and controllers to fully reproduce the layout of the aircraft being simulated. The large size of the aircraft allows for more than one evaluation pilot and extra engineering observers on a flight as well as sufficient space for any additional equipment required.

TIFS Simulation Programmes

The TIFS has been used in numerous flying qualities research programmes many of which are covered in the literature reviews given in the appendix.

As with the NT-33A the aircraft has been used to evaluate the flying qualities of several aircraft prior to first flight, and to fine tune problems with FCS designs uncovered either during development or flight test. These aircraft are generally of the larger variety, or require the additional capabilities that are offered by the full six degrees of freedom simulations possible with TIFS.

Programmes for which TIFS has been employed include the Rockwell B-1 development, several simulations in support of the Space Shuttle programme between 1972 and 1985, BAC/Aerospatiale Concorde certification for the FAA, the Compass Cope RPV autoland, NASA twin fuselage research aircraft, Grumman X-29 development and pilot familiarisation, Boeing 7J7 sidestick tests, Northrop B-2 Stealth Bomber and Northrop/McDonnell Douglas YF-23 Advanced Tactical Fighter development. TIFS has also been used in numerous large aircraft flying qualities investigations, most recently in support of the McDonnell Douglas MD-12.

3.3 Lear 24F

The Lear 24 was purchased by Calspan in 1979 from Gates Learjet who had used the aircraft as a testbed for 51,000 feet altitude certification and other projects. Originally a Lear 24B, the aircraft was converted into a variable stability In-Flight simulator by the Calspan Flight Research Department under joint funding from the US Air Force and Navy test pilot schools, and designated a Lear 24F. While the right hand evaluation pilot's controls have been replaced with a variable feel centre stick and rudder, the left hand safety pilot/tutor's controls remain those of the conventional Lear which are directly connected to the control surfaces and are always available to the safety pilot.

The aircraft replaced the two variable stability McDonnell Douglas B-26s previously modified and operated by Calspan for the same purpose. The Lear 24F is fully utilised in its teaching role at the US Air Force and Navy test pilot schools.

The following sections describing the Lear 24F are reproduced from the Calspan aircraft description brochure.

System Design

In Calspan's Learjet, the basic aircraft stability characteristics are modified through a response-feedback flight control system. Acting through the aircraft's primary control surfaces, the system is driven by electro-hydraulic servo actuators. In addition, a variable feel system, affecting the pilot's stick and rudder force and motion cues is incorporated, figure 7.

The variable-stability response-feedback flight control system senses body axis linear accelerations, rotation rates, and attitudes, feeding them to the appropriate control surfaces through variable feedback gains. Angle of attack, sideslip and their rate of change are also provided as feedback quantities. Pilot command inputs from the right-seat centre stick controller are summed with these feedback signals and sent to electro-hydraulic servo actuators to position the control surfaces, figure 8. These actuators operate independent of, but parallel to, the normal Learjet flight control system.

The variable feel system provides the pilot with the desired stick and rudder pedal forces, displacements and gradients. This is accomplished using electrohydraulic servo actuators attached to the right-seat centre stick and rudder pedals, allowing the simulation of a reversible or irreversible control system. The effective gearing between the cockpit control motion (or force if chosen) and control surface deflection can be altered. Circuitry between the feel system and the flight control system allows the insertion of lead/lag, transport time delay, and freeplay between the cockpit control input and the control surface motion. In addition, the frequency, damping ratio, and force gradients may be varied in flight for the centre stick. Preload, friction, non-linear gradients, downspring, and bobweight effects are incorporated as well. The side stick controller has somewhat less variability in its feel characteristics. In either case the control surface motions are not apparent to the evaluation pilot, allowing the safety pilot to change both aircraft and feel system dynamics without the evaluation pilot being aware of the manner in which the changes are being made.

A digital configuration-control system provides the Calspan safety pilot with an on-line interface, allowing full control of all feel characteristics, command gains, feedback gains, and non-linear characteristics. System capability consists of 128 pre-programmed configurations readily accessed in flight plus another 128 configurations that can be set up in flight and saved for later recall.

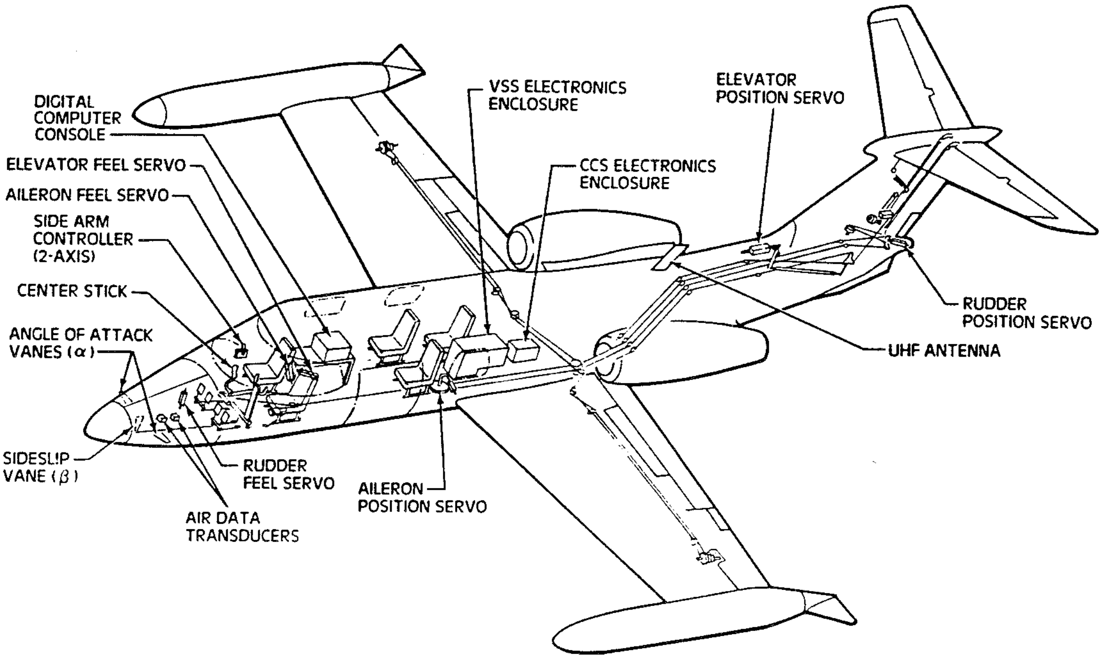


Figure 7. Lear 24F Major Component Location

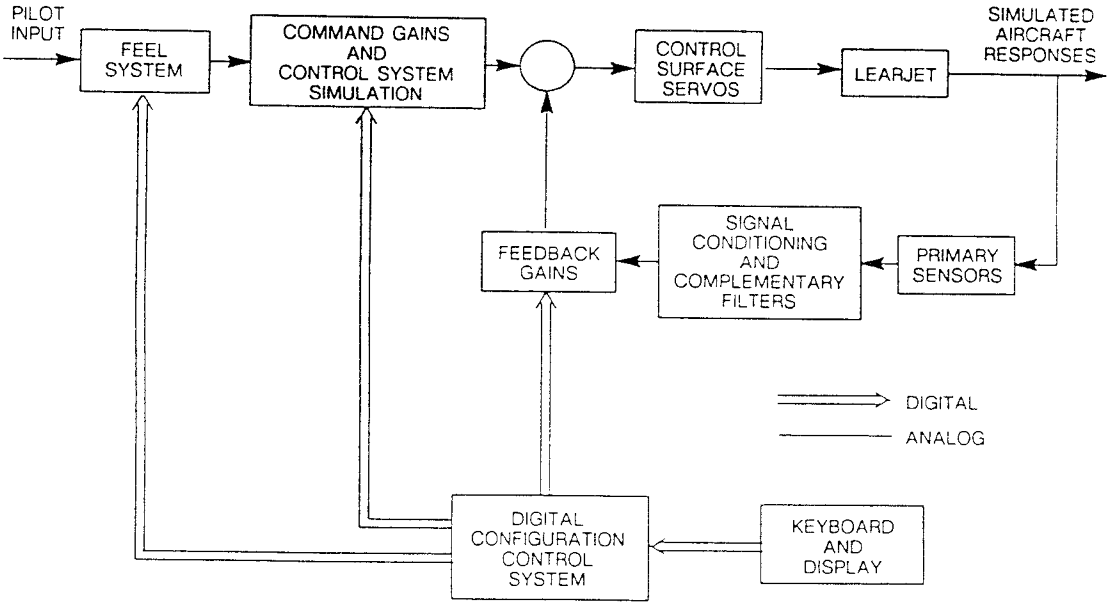


Figure 8. Lear 24F Variable Stability Block Diagram

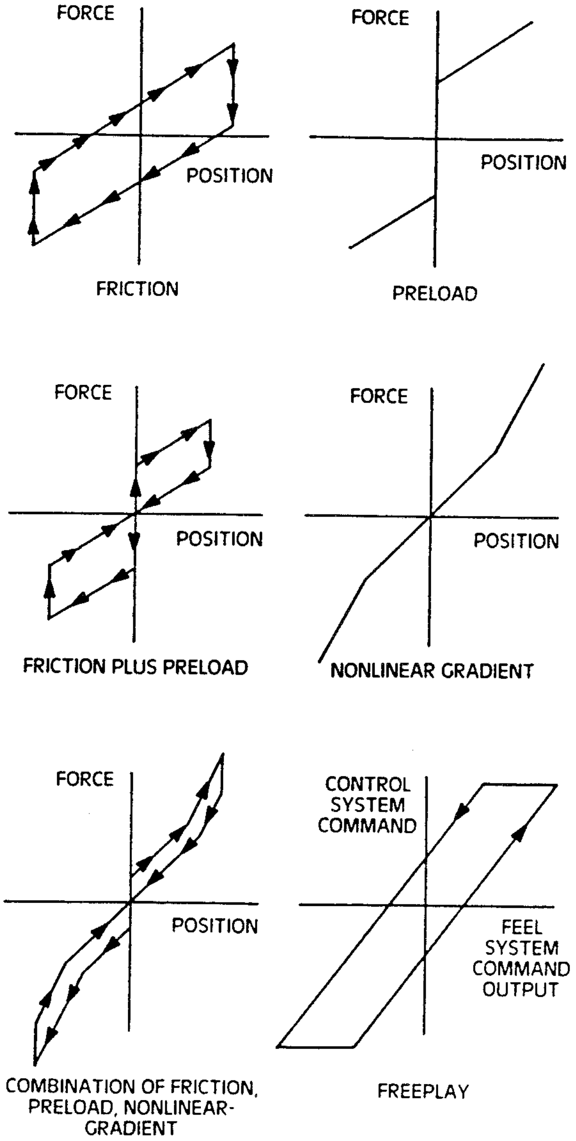


Figure 9. Feel System Non-Linearity Characteristics

Capabilities

A very wide and representative range of dynamic responses can be simulated using the Learjet variable stability system. For example short period frequencies as high as 12 rad/sec or Dutch Roll frequencies up to 5 rad/sec can be generated. Damping of the oscillatory aircraft response modes can be varied from damping ratios greater than one to highly divergent. The aircraft can be made statically or dynamically unstable in either pitch or yaw. The roll response can be varied from very quick to extremely slow. Adverse and proverse yaw can be added, and dihedral effects can be varied over a wide range. An unlimited combination of responses and control system characteristics can be generated to simulate almost any aircraft configuration. A single aircraft characteristic may be varied to show its effects on handling qualities with all other characteristics remaining fixed. Control system designs may be refined by selecting variable lead/lag prefilters, preloads, time delays, or non-linear force gradients, figure 9.

A special computer allows a specific aircraft's flight control system to be easily modelled. This flight control system can then be combined with the normally modelled dynamic characteristics of the aircraft, thus allowing specific flight control system changes to be evaluated. Access to all the aircraft's sensor outputs allows easy programming of new configurations. This option has allowed examining a "fly-by-wire" type control system, for example, and interfacing it with the variable stability system to provide a means of evaluating total aircraft response in a high gain environment such as flare and landing. An on-board computer interface allows real-time monitoring of selected parameters, all of which may be recorded on an AR 700 digital data recorder. A telemetry capability also exists to transmit data to a ground support station.

Current plans are to replace the existing computer used for special projects with a high-power digital computer with interactive graphics. This will allow a more versatile programming and complete simulation capability.

3.4 Lear 25

Because the Lear 24F is so extensively utilised in its service to the US Air Force and Navy, the Calspan ATC purchased a second Learjet, a Lear 25 which had also been used previously for flight test work by the Learjet Corporation. The Lear 25 was modified by the Flight Research Department to meet expanding variable stability needs and entered service in 1991.

The aircraft is used to augment the activities of the Lear 24 and has undertaken tours to Europe during the last two years to be used by, amongst others the French test pilot school, Ecole du Personnel Navigant d'Essais et de Reception (EPNER) at Istres, and ITPS at Cranfield.

In addition the Lear 25 offers in-flight simulation in the context of research and development programs. In other respects the variable stability system is almost identical to that of the Lear 24F.

4. LITERATURE SEARCH

Over 40 of the most relevant Calspan reports were reviewed. Their applicability to this study varied from being of no appreciable significance to being highly relevant. Detailed reviews were made of half of the reports viewed, containing mainly edited extracts from the original reports, and can be found in the appendix referenced alphabetically in chronological order.

Most of the papers concerned research programmes that utilised either the TIFS or NT-33A aircraft. As well as covering handling qualities research and FCS development and implementation they also cover human factors matters such as displays and effectors (references 1, F, K, N, O).

One of the most relevant papers was a review of "Flying Qualities in The Time Domain" by Rynaski, reference P. The review, performed in 1984, addressed many issues. He states that time history envelopes have become widely used for longitudinal flying qualities criteria because augmented aircraft no longer exhibit the conventional dynamics of existing criteria and because time history envelope evaluations are quick and easy. With the increasing use of ground simulators for evaluation and criteria development, the response envelopes tended more towards requirements on pitch response, which can easily be represented in ground simulators, whereas normal accelerations are reproduced very poorly and so have received less consideration. However since acceleration cues associated with the aircraft flight path response contribute significantly to, and sometimes dominate, the pilot opinion of the flying qualities, it is clear that the use of pitch response only criteria are inadequate.

Rynaski also states that the long term or phugoid-like response appears to be critically relevant to flying qualities. Of particular importance is the magnitude of the residue in each of the response variables of pitch, angle of attack and speed change. He concludes that angle of attack is the fundamental short term response indicator for flying qualities evaluations during the approach and landing. His main conclusion is that angle of attack response can usually be considered a primary indicator of flying qualities, and that the closed loop system should contain only four significant poles, of which two should satisfy the short period requirements of MIL-F-8785C and therefore dominate the short term angle of attack response of the vehicle to a pilot command.

There has been much discussion over the years as to the benefits of in-flight simulation over ground simulation (references 2, 3, 4 and U). Several papers considered this matter. DiFranco in 1968, reference B, observed that aircraft configurations with significant PIO tendencies were rated poorer in-flight, while configurations with little or no PIO tendencies were rated better in-flight. He concluded that when evaluating PIO tendencies, ground simulator results are not conservative and can be very misleading. In a TIFS study to validate the performance of the NLR moving base simulator, reference K, it was observed that where significant normal accelerations were generated pilot ratings were not as good in the TIFS as in the ground simulator which could not reproduce these motions. However for the low pitch frequency configurations the TIFS simulation resulted in better ratings than the ground simulator. It was suggested that this could be due to the subtle real world motion and visual cues which aid in flying these lower responding configurations.

During an NT-33A study into Landing Approach Higher Order Systems, reference G, it was found that for aircraft with significant control system dynamics, the landing task, or flare and touchdown is the critical task. In particular the last 50 feet were found to be most critical, and it is concluded that landing approach flying qualities evaluations must therefore include actual touchdowns, in a realistic environment, to be valid. It was further found that significant control system lags create PIOs in the landing task but not the approach, while basic aircraft problems such as low short period damping or low static stability do not create PIOs in the landing task.

It was found in reference B that the deterioration in the pilot ratings with an increase in the delay parameter does not appear to be a function of whether the delay arises from the feel system, elevator actuator or both. However pilot comments differ depending on the source of the delay. In the investigation undertaken in reference U it was observed that in flight the flying qualities degraded from level 1 to level 2 beyond 150 msec of total delay from pilot input to visual cue. Beyond 150 msec flying qualities degraded at approximately 1.5 rating units per 100 msec of added delay.

The move to aircraft with SCAS designs of increased order of the overall system was considered unnecessary in reference E. It concluded that in its investigation good augmentation aircraft configurations were obtained without increasing the order of the transfer functions. Moreover it was found in reference L that the closed loop pitch attitude bandwidth requirements for large civil aircraft is less than for fighters, with a value of 1.5 rad/sec suggested. It was found in the investigation that the evaluation 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 and heavy aircraft, and were therefore able to accept longer time delays.

In reference C it was found that pilots tend to fly a poorer configuration more tightly than a good one because they are afraid of "losing it". With a relatively well behaved configuration they will tolerate more error since recovery is easier. The question of what kind of commanded response a pilot prefers, or requires, to flare and land an aircraft with precision has commanded much attention, for example reference T. What is becoming clear from much of the work undertaken is the desire of the pilot for the aircraft to exhibit alpha stability. This is not a new idea and was one of the conclusions of Chalk in 1966, reference A. However the question of how best to achieve an acceptable mechanisation to obtain alpha stability is still being investigated.

In an investigation into the longitudinal flying qualities of fighters, reference E, it was found that those FCS designs which incorporated alpha feedback provided satisfactory flying qualities in all flight phases evaluated. During an investigation into pitch rate flight control systems for the flared landing tasks, reference Q, it was concluded that good attitude control, although a prerequisite for the flared landing task, is not sufficient to provide level 1 performance. The report suggests that pilots require surrogate feedback cues to precisely control flight path in the landing flare. Although it suggests several ways of providing these cues it concludes that the most direct way is to utilise angle of attack and pitch rate feedback to achieve "conventional" short period and phugoid characteristics. Recent work on large civil aircraft flying qualities supported by McDonnell Douglas, reference W, has looked at alpha, theta and gamma command systems. Although the pilot ratings did not reflect a clear preference for one law over another, the gamma command system exhibited a poorer response to turbulence yielding undesired uncommanded pitch activity.

Calspan have addressed many human factors issues both in independent studies and as peripheral factors to other investigations. In 1968, reference B, it was found that pilots were very aware of poor feel system characteristics especially when the feel system frequency is lowered and approaches that of the airplane short period. In the investigation on the use of sidestick controllers reported in reference F it was found that the best configurations evaluated were those that had low control force response gain and a small amount of stick motion.

Several investigations have been performed using the NT-33A to investigate different HUD and HDD display formats. In addition the Peripheral Vision Display (PVD), or Malcom Horizon, was fitted to the aircraft, reference O. The TIFS was used for a preliminary study of the Command Flight Path Display (CFPD) system, reference N, making use of the space available for the large amount of equipment required for the experimental system.

5. LEAR FLIGHT

The demonstration flight was performed in the Lear 24F on the 23 September 1992. The safety pilot was Calspan Engineering Test Pilot Paul Deppe. Clayton Shisler operated the video camera.

The flight (Lear 1 flight 4475) departed the Greater Buffalo International Airport at 18:30 GMT due north to work the area inland of the south shoreline of Lake Ontario between flight levels 140 and 160 for the up and away tasks. The first five approaches were performed at Niagara Falls International Airport, the sixth and final being performed on the return at Buffalo.

Descriptions of the demonstrations follow.

5.1 Up and Away Tasks

5.1.1 Static Stability Demonstration

The purpose of this demonstration was to show what effect altering the static stability of the aircraft has on the dynamic stability.

The test input was a pitch doublet, forward on the stick, back twice as far, then forward to the initial centre position and release. In order to excite the short period mode the frequency of the input must match that of the dynamic mode of motion.

As with most demonstrations the first configuration tested was the baseline Learjet. This acts as a datum to which the modified configurations can be compared. Input of the pitch doublet produced an oscillatory response with two overshoots. The damping ratio of this response was 0.5 with a natural frequency of 4 rad/sec.

Via the VSS the centre of gravity of the aircraft was moved forward, increasing the static stability of the aircraft, and the test repeated. Because this alteration increases the natural frequency of the short period it was necessary for the input to be quicker in order to excite the mode. The response of the aircraft was again oscillatory but compared to the baseline Learjet the natural frequency was increased and the damping ratio decreased. In addition increased static stability requires a larger input to disturb the aircraft. This was noticeable in that considerably higher stick forces were required for the pitch doublet, compared to the case of the baseline Lear.

The centre of gravity was next moved aft of baseline, but forward of the neutral point, producing a relaxed static stability aircraft. With this configuration the response was still oscillatory however with a reduced frequency and the motion was well damped. As the nose is raised and the stick released it "comes back slower" than the previous examples, but the aircraft retained its static stability. As expected the stick forces were lighter than the baseline Learjet.

The centre of gravity was then moved to the neutral point. In this example a small step input in pitch was made and then the stick released. Initially the nose rose at a constant rate until the stick was released, at which the pitch motion stopped and the aircraft held its attitude. Thus placing the centre of gravity at the neutral point produced a pitch rate command attitude hold system. In fact the system was not perfect because the aircraft was slightly out of trim and the centre of gravity position was only approximate.

In this configuration the aircraft was then used for a pitch pointing task by positioning the crosshairs on the windscreen on a point on the horizon. The aircraft was found to be good for this task as it is easy to hold attitude.

Lastly the centre of gravity was moved behind the neutral point to produce an unstable configuration. In normal flight the aircraft could be controlled by continuous small inputs. However when a small step input of back pressure on the stick was made the nose rose to give an exponential increase in pitch rate, the VSS automatically disengaged before recovery was initiated.

In this demonstration the centre of gravity was moved from a forward position, which produced a very springy response, to an aft position which produced an unstable divergent response. Clearly as the static stability is altered, so is the dynamic stability. This is due to the aerodynamic derivative M_α, which is a measure of static stability, having a strong influence in the frequency term of the short period and so also affecting the damping ratio.

5.1.2 Command Gain Demonstration

A basic pitch pointing task was used for this demonstration. Again the task was to put the crosshairs, or pipper, on a cloud or the horizon and hold them there. Firstly the task was performed with the baseline Learjet to act as a datum.

The command gain was then decreased. This configuration required considerably more force on the stick, and produced a slower aircraft response. However it was possible to hold the target accurately.

Next the command gain was increased to a very high value. This time the stick forces were much lighter, and the aircraft response was more oscillatory, it was quicker to put the pipper on the target but harder to hold it there because of the oscillatory response.

Changes to the command gain makes the aircraft feel very different and can mask the underlying dynamics. The dynamics of the aircraft remained constant throughout the demonstration, however the response to the pilot seemed slower for the first case and quicker for the second. This must not be confused with a lower or higher frequency short period.

5.1.3 Stick Motion Demonstration

This demonstration used the same pitch pointing task as the previous one, and the same baseline Learjet.

Firstly the stick was fixed in pitch so that it was unable to move, thus behaving as a force input stick. The aircraft response was much twitchier, felt quicker and was more oscillatory once on target and was therefore harder to keep the pipper on the target.

The stick was then set to reproduce very large motion in pitch. With this configuration it was easy to keep the pipper on the target, but a lot of movement was required. The aircraft felt slower, however the dynamics were not unpleasant, just slower to get there. The aircraft Dynamics were in fact not slower or of lower frequency than the baseline aircraft, just larger stick motions were required.

It is clear from this demonstration that stick motion can easily mask the underlying dynamics of the aircraft.

5.1.4 Angle of Attack Command

This demonstration looked at the response of the baseline alpha command Learjet as a comparison for the following configurations. The task was a simple pull-up and release. When the stick was released the attitude dropped back as the inherent alpha stability brought the aircraft back to the trim angle of attack, a characteristic known as theta droop. The pitch attitude of the aircraft was restored to that before the input was made.

5.1.5 Feedback Effects

The configuration was altered to a baseline generic relaxed static stability aircraft. A pitch doublet was input which produced a very lightly damped and quite uncomfortable oscillatory response.

In order to improve the response of the aircraft several feedback loops were incorporated into the FCS. Firstly alpha feedback was added to increase the frequency of the short period mode and so quicken the response. A pitch doublet produced a very oscillatory response. The frequency of the oscillation was increased, however the damping ratio was decreased producing a very lightly damped response, almost zero damping. In addition the stick forces were a lot higher.

In order to increase the damping pitch rate feedback was then added. A normal pitch doublet produced a minimal response, with the stick forces being "much much higher" than previously. Clearly, however, the damping ratio was increased as desired, while the natural frequency appeared to be the same as before. The solution to the high stick force problem was to increase the command gain. The combination of these three modifications produced a very well damped response which was well behaved and a vast improvement on the original baseline relaxed static stability configuration.

5.1.6 Pitch Rate Command IPP

An Integral Plus Proportional (IPP) pitch rate command system was implemented. An initial assessment found it to be a good rate command system which "stops where you put it".

The aircraft was positioned in a twenty degree banked turn and a constant input of a couple of pounds back pressure applied to the stick. This produced a steady pitch rate and as the speed decayed the normal acceleration level dropped off.

In general pitch pointing tasks it was found to stay exactly where it was put, performing much better than the neutral point demonstration because the loop was closed much more tightly.

"Step in, step out, stops like a rock."

5.1.7 Normal Acceleration Command IPP

The next implementation was that of an IPP controller acting on normal acceleration. A nose down step input, then release while less than 1g, resulted in the nose rising to seek 1g.

A small nose up input, then release while greater than 1g, and the nose drops to seek 1g. However when the nose was raised to 20 degrees and released it initially dropped back a little, but then as this action caused the normal acceleration level to drop below 1g, the nose rose to seek 1g.

The aircraft was then positioned in a twenty degree banked turn as in the previous demonstration. Again a steady back pressure of a couple of pounds was applied to the stick to maintain a constant g level, however this time the pitch rate increased

5.1.8 Aileron Actuator Rate Limiting

The aircraft was returned to the baseline Learjet and an actuator rate limiter was simulated by the VSS. The task for this demonstration was bank angle capture.

Initially the aircraft was rolled gently to a twenty degree bank angle, held in that attitude and then returned to wings level. No problems were found and the aircraft handled well with light stick forces required.

The task was then repeated more aggressively. The initial input was made and then reversed at the target bank angle in order to hold that attitude. Immediately a "big time PIO" resulted and continued until the stick was released, at which point, as the pilot backs out of the loop, the aircraft quickly settled.

5.1.9 Gain Scheduling

The baseline Learjet was trimmed at level flight at 250 knots. A long roll mode time constant representative of a large aircraft was then added. This was assessed using a bank angle capture task and found to exhibit a considerable delay, being slow to respond. It was therefore necessary to make the inputs before the response was required.

To correct this a zero was added to the FCS to cancel the slow roll mode pole and a new pole was added further from the origin, thus producing a faster response. This was tested using the same task and the response was found to be much crisper, making a simple step in and step out in roll. The effective time constant was much quicker and the aircraft was much easier to handle.

The aircraft was then slowed to 140 knots, with the flaps lowered to 20 degrees, and trimmed for level flight. The FCS remained unchanged, however when the bank angle task was repeated the original long roll mode time constant had returned.

Therefore although the pole and zero were good for 250 knots, they were incorrect for 140 knots with 20 degrees of flap. This demonstration graphically shows the importance of correct gain scheduling.

5.2 Approaches

The first five approaches were made to Runway 28R at Niagara Falls International Airport. The first approach was a long run in with the aircraft being handed over in the landing configuration, gear down flaps 20 degrees, on a long approach on localiser and on the 2.5 degree glide slope. The aircraft was left in this configuration throughout the right hand circuit pattern, flown at an altitude of 2000 feet on the QNH, approximately 1300 feet AGL. Runway 28L using a left hand circuit pattern was active throughout the period. Configurations were changed and the aircraft handed over on the downwind leg, the safety pilot taking control again either just prior to or after touchdown. The minimum approach speed was set at 125 knots. The wind was given as 320/10 producing a slight cross wind from the right requiring slight correction.

Due to a flight of F-16s in the circuit at Niagara the final approach was cancelled and performed instead on the return to Buffalo, flying a wide left hand circuit to runway 05 in order to avoid the Goodyear Blimp on finals.

5.2.1 First Angle of Attack Command

The aircraft was handed over in the landing configuration on a long approach. The configuration was a basic alpha command system similar to the unaugmented Lear. The main purpose of both this and the second approach was to become familiar with the handling of the aircraft.

The VSS system was accidentally disengaged after flare just before touchdown. Otherwise the approach and landing were good. Although obviously different to the light aircraft on which previous experience had been obtained, the aircraft's handling characteristics posed no great problems to perform the task required.

5.2.2 Second Angle of Attack Command

The aircraft was handed over on the downwind leg of the right hand circuit. It exhibited a tendency to easily pick up speed and to climb, especially in the turns, however this was due to inexperience with the type of aircraft rather than a deficiency of the FCS, and a problem with setting and maintaining the correct attitude for constant altitude. Due also to traffic on 28L and a tight approach with a very short final the aircraft was not ideally set up for the landing. Although glide slope and localiser were established prior to the flare, the speed was approximately 10 knots fast. As a result the aircraft exhibited a tendency to float which had not been anticipated. This however was almost certainly due to the excess speed and not the FCS. Otherwise the aircraft handled as expected and posed no great difficulty to control or land.

5.2.3 First Pitch Rate Command IPP

After taking control on the downwind leg, due to the experience gained on the previous circuit, recognition and maintenance of the correct attitude resulted in tighter altitude control and this was not an issue in any of the subsequent circuits. Review of the video tape after flight showed less of a tendency for the view through the windscreen to oscillate compared to the alpha command system. Although this effect was not noticed in flight after due consideration it is believed that this is a feature of the FCS and that the pitch rate command system did produce a visibly more stable platform.

Due to the problems with the previous approach a longer approach was used subsequently. As a result the aircraft was better established prior to the flare, control during the approach causing no problems. Flare was initiated with a back pressure applied to the stick conventionally, but as the nose rose the back pressure was released to avoid overflaring, and the aircraft held the nose high attitude. The aircraft floated in this constant attitude for a considerable time, and although this felt strange, with no stick input, no attempt was made to push forward on the stick. The horizon was not visible on the video due to the attitude, whereas this was not the case for the alpha command system.

With constant attitude and angle of attack held by the FCS the speed decayed and due to reducing lift the aircraft descended. However due to a slight over flare initially the aircraft was slightly high and as speed continued to decrease the safety pilot took control at touchdown, completing the landing before applying full power.

5.2.4 Normal Acceleration Command IPP

As with the pitch rate configuration, the normal acceleration command system appeared on the video to give a smoother ride than the original alpha command system. The same circuit and approach procedure were flown with no difficulty in controlling the aircraft. In the approach it felt "fairly stable" with no appreciable difference to the earlier configurations.

The noticeable difference came in the flare. The initial flare was made, and again the back pressure on the stick had to be released to stop the aircraft overflaring. The attitude was maintained constant much the same as for the pitch rate command system, however this time the aircraft floated far more dramatically. Again the speed decreased, leading the safety pilot to take control just before the aircraft touched down.

The appreciation of the floating tendency on this occasion was more of a gut feeling of "hanging there". Although the floating tendency is clearly visible on the video, the visual cue was not dominant in the appreciation of the problem. The overall effect for the pilot was a combination of the visual and motion cues as well as the foreign tactile feel of little or no back pressure on the stick.

5.2.5 C*u Command

The final configuration was an implementation of a C*u controller. This was much the same as the normal acceleration system flown previously (which incorporated some pitch rate feedback to ensure sufficient damping), but included feedback of forward speed.

Although there were no problems with altitude control on the downwind leg, the video shows a less stable platform similar to the original alpha command systems, rather than the previous two configurations. Again this was not noticed in flight.

The noticeable difference on the approach was the considerable back force required on the stick as the speed decreased, and the need to retrim. This was due to the speed stability which results from the feedback of forward speed. Considerable back force was required during the flare however good control was maintained throughout the flare and the aircraft was easy to land. Its handling was similar to a conventional aircraft.

5.2.6 Second Pitch Rate Command IPP

The second pitch rate command system approach was made since the first had not demonstrated the anticipated physiological effects as well as the normal acceleration configuration, coloured in part to the experience of the second alpha command approach.

Following an off centre line approach to Buffalo, caused by manoeuvring to avoid the Goodyear Blimp, the aircraft again exhibited a severe tendency to float, producing similar gut feelings to the earlier normal acceleration system.

6. CONCLUSIONS

The importance of in-flight simulators in handling qualities research cannot be overstressed. It is clear from both the mass of reports reviewed and from experience gained during the flight in the variable stability Learjet that ground simulators do not reproduce the full physiological and psychological effects of piloted flight. This is especially apparent during the landing flare, where these effects are critical to an assessment of an aircraft's handling qualities.

The information obtained from the review of Calspan's reports is invaluable to this study. The detail available in the reports could not have been obtained so readily locally, and the sheer volume of reports reviewed could not have been performed in such a short time. Although much of the information refers to military aircraft, the concepts are highly applicable to future civil aircraft. In particular the report by Rynaski, reference P, is considered to be of great importance to this study.

Conversations undertaken with Calspan personnel proved to be of great value. A clearer understanding of the C* control law and the introduction of the C*u control law were obtained. Areas were identified that should receive attention during this study, and in particular the importance of the inter-relationship between angle of attack, pitch attitude and flight path in controlling an aircraft were stressed, as was the pilot's awareness of the aircraft's angle of attack.

Contact was made with the Stability, Control, Simulation and Flying Qualities Technology Group of the McDonnell Douglas Corporation with the view to future cooperation. As a result of this the Group's Leader visited the CoA in October to review possibilities for future collaboration.

The engineering test flight in the variable stability Learjet demonstrated features of modern FCS design that could not be demonstrated elsewhere. The up and away tasks demonstrated many important features and the need for correct design of the total FCS.

The main purpose of the flight, however, was to compare the different command systems in the landing approach task. The effect of the pitch rate and normal acceleration command systems were similar, both producing an unfamiliar attitude hold with no stick input and a tendency to float after the flare.

It is clear that these configurations produced undesirable cues in the flare which could not be reproduced in a ground based simulator. Had these approaches been performed in such a simulator it is expected that desired performance could easily be attained. It was the motion cues that identified these systems as producing undesirable physiological effects for the pilot.

The C*u command system behaved more conventionally exhibiting speed stability in the approach, with the associated need to retrim. In the flare there was a continual need to apply back pressure to the stick to hold the angle of attack, thus handling like a conventional aircraft. It is therefore considered that the C*u control law shows great potential for future applications to civil aircraft.

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APPENDIX

REPORT REVIEWS

A. Chalk, Charles R, "Flight Evaluation of Various Phugoid Dynamics and $1/T_{h1}$ Values for the Landing Approach Task", CAL Report No. TC-1921-F-4 (AFFDL-TR-66-2), February 1966

The program consisted of several configurations of drag, short period and phugoid characteristics established through the NT-33 variable drag and variable stability systems. The piloting task was to fly a constant speed approach consisting of a straight-in IFR portion, followed by transition to a visual glide path defined by an arrangement of lights. The approach was then terminated with a waveoff, which was followed by a visual circuit of the airfield and a second visual approach on the glide path with the same configuration.

Conclusions.

1. The pilot preferred the higher frequency short period of 2.46 rad/sec to that of 1.46 rad/sec. The configurations with the less stiff short period did not readily maintain the trim angle of attack or attitude, thus the pilot had to provide nearly continuous attitude stabilisation to maintain precise flight path control. In addition, he had to overdrive the airplane to obtain satisfactory attitude response when manoeuvering.

2. Increasing the phugoid frequency resulted in increased stick force feel for airspeed deviations from trim. In smooth air this helped the pilot sense airspeed errors without looking at the airspeed indicator. In turbulence, however, the pitch response to airspeed fluctuations (caused by horizontal gusts or wind shear) became detrimental to the task of flight path control and tended to outweigh the advantage of stick feel for airspeed changes. Limited data obtained for reduced phugoid frequency indicates that the lack of stick force for airspeed changes from trim was not a strong factor in pilot rating; however, when the phugoid mode was made statically unstable, the pilot rating degraded sharply because of the amount of closed-loop control required, and because of the danger that errors might grow beyond the control authority available. A configuration with time to double amplitude of $T_2 = 3.57$ sec was rated PR = 8.

3. The Pilot's handling qualities rating of an airplane must consider both the response to his control inputs and the response of the airplane to external inputs such as wind gradients and atmospheric turbulence. For the configurations evaluated in this program, the pilot comments indicated that the most objectionable characteristic was the pitch response to airspeed variations caused by wind shear and turbulence.

4. For positive values of $1/T_{h1}$ the pilot accepted (i.e. PR = 6.5) unstable phugoid configurations with times to double amplitude of $T_2 = 12$ sec for $\omega_p = 0.32$ rad/sec and $T_2 = 17$ sec for $\omega_p = 0.15$ rad/sec. However the pilot in these tasks was able to operate in a continuous closed-loop manner when required since he had no other tasks to perform. When peripheral tasks such as map reading become appreciable the pilot shall not be able to control the attitude so accurately. The pilot rating improved as the phugoid mode was made more stable, however increasing the phugoid damping ratio beyond $\zeta_p = 0.15$ did not further increase the pilot rating for the landing approach task.

5. The pilot's acceptance of a certain level of speed stability must be coloured by the overall difficulty of controlling the aircraft, which determines the amount of attention he can devote to the speed control problem. The results of this

experiment have confirmed that when $1/T_{h1}$ is negative it becomes a primary handling qualities parameter for the landing approach task.

B. DiFranco, Dante A, "In-Flight Investigation of the Effects of Higher Order Control System Dynamics on Longitudinal Handling Qualities", CAL Report No. BM-2238-F-4 (AFFDL TR-68-90), July 1968

The study used the NT-33A IFS to investigate HOS response characteristics obtained by altering the elevator stick feel system dynamics and the elevator actuator dynamics in conjunction with four different sets of longitudinal short period airplane dynamics. Three were investigated as a fighter in up and away flight, the fourth as a fighter in landing approach. Over thirty different configurations were evaluated by two pilots.

The results of the investigation indicated that many of the higher-order control systems investigated produce very pronounced PIO tendencies and these tendencies can be related to the delay in the initial response of the airplane and to the stick force gradients. Configurations that were acceptable with conventional control system dynamics were considered unflyable with certain higher-order characteristics.

Conclusions.

1. The predominant pilot comments on many of the control system configurations were concerned with the delay or lag in the response following a control input and the PIO tendencies of the configurations.

2. Some of the higher-order configurations simulated and evaluated were considered unflyable by the pilots and were given pilot ratings of 10 and PIO ratings of 6. These configurations usually had large amplitude and divergent PIOs with any closed-loop control.

3. A strong correlation exists between the pilot ratings and PIO ratings of the configurations. The deterioration in handling qualities with degraded control system dynamics is therefore related to an increase in PIO tendencies.

4. With higher-order control system dynamics, the airplane short period response to step force inputs can be reasonably well represented by a time delay and an equivalent second-order response. The time delay and frequency and damping of the equivalent second-order response are determined by matching the lowest-order coefficients of the characteristic equation of the higher-order system. This simplified representation is poorest when the lowest frequency of the control system is near the airplane short period frequency. When the control system frequency is significantly higher than the airplane short period frequency, the equivalent second-order response is essentially the airplane short period response.

5. It is also possible to compute a delay time from a match of the highest-order coefficient in the characteristic equation of the higher-order system. This delay time is approximately half the delay time determined by matching the lowest-order coefficients. It is also possible to determine a delay time from the control system phase shift at the airplane short period frequency. The phase shift delay time is comparable to the delay time obtained from a match of the coefficients of the lowest-order terms.

6. Pilot ratings and PIO ratings for all the configurations simulated correlate reasonably well with a computed delay parameter (a_{LF}/P_E). a_{LF} is the delay time and P_E is the period of equivalent second-order response determined from a match of the coefficients of the lowest-order terms in the characteristic equation of the higher-order system.

7. The delay parameter is reasonably well correlated to control system phase angle evaluated at the airplane short period frequency. It is therefore also possible to correlate pilot ratings and PIO ratings to control system phase shift at the airplane short period frequency.

8. There is some indication from tracking records that tracking difficulties and PIO tendencies can be related to the phase angle of the control system at the airplane short period frequency.

9. The deterioration in the pilot ratings with an increase in the delay parameter does not appear to be a function of whether the delay arises from the feel system, elevator actuator, or both. Pilot comments differ however, depending on the source of the delay.

10. It is evident from the pilot comments that pilots are very aware of poor feel system characteristics when the feel system frequency is lowered and approaches the airplane short period frequency. Pilot complaints are then directed to the "high inertia", "rate limit" or "soft" characteristics even when they think they do not interfere with airplane control.

11. When the response delay arises primarily from the elevator actuator, the handling qualities are considered poorer by the pilots during VFR flight. When the response delay arises primarily from the slow elevator stick, the handling qualities appear to be poorer under IFR flight. Insufficient data exists to completely substantiate the latter statement.

12. Pilot ratings and PIO ratings are related to the stick force gradients (F_{ES}/n_z) of the configuration. A configuration with significant PIO tendencies can be made unflyable by lowering the stick forces, and an unflyable airplane may be made flyable by raising the stick forces. Higher stick forces do not eliminate the PIO tendencies, but they do reduce the amplitude of the oscillations and can prevent them from being divergent.

13. The effect of reducing the airplane short period damping is to degrade handling qualities at a higher rate with an increase in the delay parameter. The lower short period damping appears to accentuate PIO tendencies with the same delay parameter.

14. Less correlation exists between the delay parameter and the PIO tendencies for the landing approach configurations simulated. Initially, an increase in the delay parameter appears to degrade handling qualities without an increase in PIO tendencies. The data, however, is not conclusive on this point.

15. General comparisons of fixed-base ground simulator versus flight evaluations indicate that configurations with significant PIO tendencies are rated poorer in flight, and configurations with little or no PIO tendencies are rated better in flight. In evaluating PIO tendencies, ground simulator results are not conservative and can be very misleading.

C. Schultz, W C; Newell, F D and Whitbeck, R F, "A Study of Relationships Between Aircraft System Performance and Pilot Ratings", CAL Report No. IH-2748-B-1 (NASA CR-1643), January 1970

The study examined the relationship between man-machine system performance and pilot evaluation data.

The Chosen task was to fly an ILS approach between the outer and middle markers in a ground simulator. The modelled aircraft had some poor flying qualities and also side gusts were added to the simulation.

Conclusions.

1. Glide Slope rms error score does not correlate with pilot rating for the ILS task.
2. There is no apparent linear combination of rms error scores that correlates with pilot rating for the ILS task.
3. There is no correlation between glide slope rms error and phase shift at 3 rad/sec for h/δ_e, θ/δ_e and α/δ_e.
4. The analysis of variance of glide slope rms error do not indicate that this measure is as sensitive as pilot rating.
5. Pilots frequently give a lower rating because of relatively poorer performance as they approach the middle marker.
6. Pilot rating is not readily apparent from records of glide slope error. The pilots fly a poorer configuration more tightly than a good one because they are afraid of "losing it". With a relatively well behaved configuration, they will tolerate more error since recovery is easier.

D. Neal, T Peter and Smith, Rogers E, "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes", CAL Report No. BM-2821-F-4 (AFFDL-TR-70-74), Vols I & II, June 1970

The investigation looked at longitudinal control system dynamics of combat aircraft and the fighter's mission, i.e. up and away, using the NT-33A. Two pilots evaluated a total of 57 different combinations of control-system and short-period dynamics at two flight conditions. The Neal and Smith Criterion is developed as well as the application of the results to the C* criterion.

Correlation of pilot ratings with the C* Criterion was variable. One problem identified concerning the use of time history envelopes is when there is a small disagreement with the boundary, how serious is the degradation in flying qualities? For the configurations with negligible control-system dynamics correlation with the C* criterion was fairly good. However the disagreements were caused by the effects of control-system dynamics, the very effects the criterion was designed to handle.

A full derivation of the Neal-Smith criterion is given in the report.

Conclusions (reduced).

1. For the "combat" phase of a fighter's mission, those tasks which require precision control of pitch attitude will usually be the most critical, from the standpoint of longitudinal flying qualities.

2. It would appear that F_s/n_z is more of a performance parameter than a flying qualities parameter, in the sense that it forms a prerequisite to good flying qualities.

3. The results of this experiment show that the dynamic modes of the FCS can cause serious flying-qualities problems, but the data does not correlate with the control system requirements of MIL-F-8785B (paragraph 3.5.3). In addition, the C* criterion does not adequately account for control-system dynamics.

4. The results also show that low ζ_{sp} can cause PIO tendencies, which are stronger at moderate values of ω_{sp} than when ω_{sp} is high. The strongest PIO tendencies, however, are obtained when control-system lags are added to configurations having low ζ_{sp} or low ω_{sp}.

E. Boothe, Edward M; Chen, Robert T N and Chalk, Charles R, "A Two Phase Investigation of Longitudinal Flying Qualities For Fighters", Calspan Report No. AK-5280-F-2 (AFFDL-TR-74-9), April 1974

Phase I To assess different performance of tasks from original Neal and Smith work with tasks where a pilot actually tracks another aircraft. (The original work only included simulated tracking tasks.)

Phase II Developed four different FCS to criteria of Neal-Smith and MIL-F-8785 B. All four FCS received satisfactory pilot ratings for all flight phases. The FCS designs comprised:

1. α and g feedback
2. α, n_z and g feedback
3. n_z and g feedback
4. n_z and g feedback with an integrator in the forward loop, and a pre-filter with $\omega = 4$ rad/sec.

The report goes into some detail of the FCS design process and use of the criteria and so could prove a useful reference.

Conclusions.

1. It was determined that since all the tasks evaluated were generally satisfactory, the criteria are not limited to the precision tracking task; but if properly applied they will provide satisfactory flying qualities for other fighter airplane Flight Phases.

2. It is not necessary in Stability and Control Augmentation Systems (SCAS) design to increase the order of the overall system. In the investigation three of the four systems were designed using constant speed, basic airframe dynamics. In each case good augmentation aircraft configurations were obtained without increasing the order of the transfer functions.

3. The use of angle of attack as a SCAS feedback signal was demonstrated in flight to be desirable. Both systems which incorporated alpha feedback provided satisfactory flying qualities in all the Flight Phases evaluated.

4. The program demonstrated that a variety of longitudinal SCAS configurations can be designed to meet level 1 flying qualities requirements. It was suggested, therefore, that a logic could be built to switch from one system to another whenever a failure is detected in a sensor.

F. Hall, G Warren and Smith, Rogers E, "Flight Investigation of Fighter Side-Stick Force Deflection Characteristics", Calspan Report No. 5280-8 (AFFDL-TR-75-39), May 1975

Report on a limited investigation on the use of sidesticks. In particular whether motion was necessary or desirable for good flying qualities.

Conclusions.

1. Best configurations evaluated for the up-and-away and landing approach tasks were those that had low control force response gain and a small amount of stick motion.
2. The fixed side-stick controller was considered satisfactory (PR = 3.5) for the landing approach tasks but not for the up-and-away flight tasks.
3. For the up-and-away tasks, a small amount of side-stick motion was beneficial in smoothing the initial response and thus improving the flying qualities of an airplane that was considered overly sensitive with the fixed stick. A properly designed electronic prefilter could possibly achieve the same result.

G. Smith, Rogers E, "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities", Calspan Report No. AK-5280-F-12, March 1978

This program has subsequently been referred to as the LAHOS (Landing Approach Higher Order Systems) report. It addressed different short period dynamics and added additional control system dynamics to the baseline NT-33A aircraft, such as lead/lag filters and pure time delays.

Conclusions.

1. For aircraft with significant control system dynamics, the landing task, or flare and touchdown is the critical piloting task.

2. The critical area is the last 50 feet of the landing task; landing approach flying qualities evaluations must therefore include actual touchdowns, in a realistic environment, to be valid.

3. Significant control system lags create PIOs in the landing task but not in the approach task; basic aircraft problems such as low short period damping or low static stability do not create PIOs in the landing task.

4. For the landing approach task (Flight Phase Category C) the longitudinal flying qualities requirements of MIL-F-8785B(ASG) and suggested revisions are not applicable to aircraft with significant control system dynamics.

5. In general, the performance on the pitch attitude tracking task is representative of the actual landing task performance.

6. Pilots could perform the landing task with relative ease (PR 3 to 4) even with rapid longitudinal divergencies as severe as 2 seconds time to double amplitude.

7. From cursory analysis, it would appear that the pilot selects the pitch sensitivity as a function of the dominant system time constant which is an equivalent value of $\zeta\omega$.

H. Smith, Rogers E, "Equivalent System Verification and Evaluation of Augmented Effects on Fighter Approach and Landing Flying Qualities", Calspan Report No. 6241-3, August 1979

(Actual report reviewed was of the same title but: "Volume 2 - Program Plan, Test Data and Analysis", September 1981, and co-authored with John Hodgkinson and Richard C Synder of the McDonnell Aircraft Company - MCAIR)

The Equivalent systems approach was developed by MCAIR. This study evaluated its application to fighter approach and landing.

Three methods of obtaining low order representations of high order dynamics:

1. selecting a subset of the high order roots for evaluation - sometimes called the dominant root method;

2. matching time histories; and

3. matching Bode frequency response plots.

This study used the 3rd approach.

Although interesting, particularly in the application of the equivalent systems method, it is of no immediate relevance. No great conclusions were drawn, mainly recommendations for future work.

I. Chalk, Charles R, "Recommendations for SCR Flying Qualities Design Criteria", Calspan Report No. 6241-5 (NASA CR 159236), April 1980

Abstract:

"The document contains a complete set of flying qualities design criteria applicable to large supersonic cruise aircraft. The design criteria are derived from existing civil and military flying qualities specifications, recent research data and documented characteristics of operational aircraft. The extensive appendix contains background information and substantiation data for the design criteria."

The report is basically a MIL SPEC format for the Supersonic Cruise Research aircraft. Although very interesting, it is not of direct relevance to this study.

J. Radford, Robert C; Smith, Rogers E and Bailey, Randall E, "Landing Flying Qualities Evaluation Criteria for Augmented Aircraft", Calspan Report No. 6339-F-3 (NASA CR 163097), August 1980

The investigation applied several longitudinal handling qualities criteria to highly augmented aircraft. These were:

Neal-Smith (plus the Chalk modified N-S)
Onstott (by Ed Onstott of Northrop)
McAir Equivalent Systems (by John Hodgkinson)
Ralph H Smith Criterion

The investigation used data obtained from both the LAHOS and Neal and Smith investigations.

The report was analytically based using the various criteria to produce conclusions on the use of each. As such there were no overall conclusions, only recommendations. However the report is highly relevant to this study.

K. Weingarten, Norman C, "Flying Qualities Experiment Performed for the National Aerospace Laboratory (NLR), the Netherlands, in the Total-In-Flight Simulator (TIFS)", Calspan Report No. 6645-F-4, March 1981

The purpose of the investigation was to validate results of experiments performed on the NLR moving base simulator. Only the experiment is described in the report, the data analysis is covered in a separate report by NLR.

The results in the TIFS differed from those obtained from the NLR ground simulator:

1. where significant normal accelerations were generated (pitch overshoot and direct lift control) pilot ratings were not as good in the TIFS as in the ground simulator which could not duplicate these motions;

2. for the low pitch frequency and long roll mode time constant configurations, the TIFS simulation resulted in better ratings than the ground simulator. This could be due to the subtle real world motion and visual cues which aid in flying these lower responding configurations;

3. airspeed control seemed to present greater problems, or at least was noted more, in the TIFS.

L. Weingarten, Norman C and Chalk, Charles R, "In-Flight Investigation of Large Airplane Flying Qualities for Approach and Landing", Calspan Report No. 6645-F-5 (AFWAL TR-18-3118), December 1981

The objectives of the In-Flight investigation using the TIFS was to obtain data applicable to the approach and landing task for a very large (one million pound) aircraft. The primary variables were relative pilot position with respect to the centre of rotation, command path time delays and phase shifts, augmentation schemes and levels of augmentation.

The three aircraft configurations were a long aft tail, canard and short aft tail. Both angle of attack and pitch rate feedbacks were included.

Conclusions (reduced).

1. The pitch rate augmentation system was generally preferred over the angle of attack augmentation. This was especially true for configurations with the pilot behind the centre of rotation. This was due to the lower turbulence response, attitude-hold feature, and level turn capability without pitch inputs with the q-augmented configurations.

2. The pilot ratings were degraded for the cases where the pilot was located near or behind the centre of rotation.

3. The evaluation pilots tended to apply a less demanding standard of maneuorverability than for previous landing approach studies because the configurations were defined to be very large and heavy aircraft. The closed-loop pitch attitude bandwidth requirements for the landing approach task with this Class of aircraft appears to be 1.5 rad/sec.

4. The degradation caused by the time delay was less severe than in previous landing approach studies in both pitch and roll. This is primarily a result of the decreased bandwidth demanded by the pilots for this class of airplane. The present equivalent time delay requirements of MIL-F-8785C appear to be conservative for this class of airplane and flight phase. Data is presented which suggests that the amount of time delay that can be tolerated in the command path is inversely related to the dynamic bandwidth required to perform the task.

5. When the pilot position is forward of the centre of rotation, the pitch acceleration response to control provides an earlier linear acceleration cue at the pilot position that is easily perceived by the pilot and serves to confirm to the pilot that the airplane is responding to his command. When the pilot is located far ahead of the centre of rotation, the linear acceleration cue is amplified immediately following the transmission delay through the control system but before the lag associated with the short-period mode. This effect may contribute to the higher tolerance to control system time delay observed in this experiment.

6. The effect of turbulence on the unaugmented configurations was relatively low except for the long-term speed control due to its negative static stability. As the alpha augmentation level was increased, a pitching and airspeed response to turbulence became greater at frequencies below 1 rad/sec. At the highest levels of augmentation, the response to turbulence at low frequency seriously hindered control. The effect of the pilot being very far from the centre of rotation also added to the motion felt by the pilot in turbulence. As the q-augmentation level was increased, these turbulence effects became less.

This was due to the low static stability of the base airplane and the long-term attitude hold of the q-feedback configurations.

M. Weingarten, Norman C and Chalk, Charles R, "Application of Calspan Pitch Rate Control System to the Space Shuttle for Approach and Landing", Calspan Report No. 7102-F-1, February 1983

An analytical study of the existing Orbiter FCS and those proposed by Calspan and NASA Dryden using pitch rate control. The Calspan version was preferred because of the reduced time delay and simpler mechanisation. Both of the proposed new systems gave better attitude and flight path control and less time delay.

The existing design criteria for pitch rate amplitude has two problems. Firstly the limit on overshoot, and secondly the large time delay that is allowed.

Conclusions.

1. The limit on the overshoot requires high damping of the short period, but the differentiating effect of the $1/T_{\theta 2}$ parameter is suppressed. Either use first order low-pass filter on pilot's command or cause a closed-loop pole to cancel $1/T_{\theta 2}$ in the transfer function of q/q_c. The introduction of low frequency roots for the purpose of preventing pitch rate overshoot will cause limited bandwidth of the angle of attack response that can be commanded and this interferes with the pilot's capability to control the lift force and the flight path.

2. Effective time delay in response to pilot commands is a primary cause of PIOs.

N. Dittenhauser, James N; Eulrich, B J and Reynolds, Philip A, "Command Flight Path Display (CFPD) Sensor Software Development and Overall Hardware Integration in the NC-131H (TIFS) In-Flight Simulator", Calspan Report No. 6645-F-12, December 1983

The report describes the installation of hardware for the project in TIFS, it does not include the conclusions drawn from the experiment.

Resource Management Systems (RMS) (a division of Systems Associates Inc., San Diego, California) were responsible for the CFPD concept, the system design, flight test planning and the data collection and analysis.

Intermetrice Inc. (of Cambridge, Massachusettes) was responsible for the display software and the flight test data processing.

Mr. George Hoover of RMS conceived and developed the CFPD concept and was overall Program Technical Director.

The report references the final report for the results:
"Command Flight Path Display, Phases I & II, Final Technical Report", by Systems Associates Inc., Resource Management Division, Report No. R83-49, September 1983.

So far only simple tests were performed in up and away flight or the circuit. No approaches were flown.

The system has not been pursued and would require considerable development before it could be used for zero, zero landings.

O. Knotts, Louis and Gawron, Valerie, "A Preliminary Flight Evaluation of the Peripheral Vision Display Using the NT-33A Aircraft", Calspan Report No. 6645-F-13 (AFWAL-TR-84-3020), March 1984

The Peripheral Vision Display (PVD), or Malcolm Horizon, is a device which projects a thin line of laser light representing the real horizon onto an aircraft's instrument panel. The horizon line is gyro stabilised and moves in pitch and roll in the same manner as outside visual cues. The advantage of this system is that a pilot can use his peripheral vision rather than foveal vision to determine his aircraft's attitude, freeing his foveal vision for use on other tasks.

The investigation flew two USAF Test Pilot School instructors to assess the PVD while attempting a turning task.

It concluded that pilots would need more familiarity with the system before assessments should be made. The pilots took some time to become familiar with the system, suggesting use of a ground based simulator for this before progressing to an In-Flight Simulator.

No real conclusions could be drawn from this preliminary study.

P. Rynaski, Edmund G, "Flying Qualities in the Time Domain", Calspan Report No. 7205-3, August 1984

The report states that time history envelopes are used for longitudinal flying qualities criterion because augmented aircraft do not exhibit the conventional dynamics of the existing specifications, and because time history envelope evaluations are quick and easy.

As the piloted ground simulator was increasingly used for evaluation and criteria development, the response envelopes tended more towards requirements on pitch response - ground simulators reproduce normal acceleration cues very poorly (if at all). Perhaps it is not coincidental that this has led to criteria development involving only pitch degree of freedom motion.

Whereas the earlier C* criteria involved both pitch and normal acceleration, the later SST and Shuttle criteria are based only on pitch responses.

Pitch criteria can be used to evaluate ground based simulators, which can reflect pitching motions of an aircraft accurately. However, neither pitch rate criteria nor ground based simulators can be expected to accurately reflect the flying qualities of real aircraft in which acceleration cues associated with the flight path response of the airplane might be expected to contribute significantly, and often dominate the pilot opinion of the flying qualities.

Conclusions.

1. Angle of attack is the fundamental short term response indicator for flying qualities evaluations during the approach and landing phase of flight.

2. Except when normal acceleration at the pilot station is significantly affected by direct lift effects due to pilot location with respect to the centre of rotation or due to direct lift devices, then the short term flying qualities are more accurately judged by normal acceleration.

3. A time history response envelope is a valid indicator of flying qualities.

4. A pilot judges flight path angle through observation of pitch angle. If the angle of attack remains constant after the short term vehicle response to a pilot command, a pilot is able to fly precisely because flight path and pitch angle are directly proportional. Therefore proportional plus integral feedforward compensation for statically unstable aircraft is not desirable since it tends to produce a sluggish alpha response and tends to "drift off".

5. the use of only one transfer function, pitch rate, to define an equivalent system model to approximate the behaviour of the two degree-of-freedom longitudinal-verical dynamic motions of an airplane represents a disregard for the most fundamental results of the excellent research in parameter identification accomplished during the past two decades. A most basic axiom of parameter identification states that the number of independent measurements of the system dynamics must be equal to or greater than the number of degrees of freedom of motion.

6. The MAIN CONCLUSION of the report is:

   The angle of attack response can usually be considered a primary indicator of flying qualities (although not that alpha must be a feedback quantity). Angle of attack "control", as used in the report, means that the closed loop system should contain only four significant poles, two of which should satisfy the ω^2n vs n/α requirements of MIL-F-8785C and therefore dominate the short term angle of attack response of the vehicle to a pilot command.

One of the recommendations concerns residue effects:

3. Long term or phugoid-like modes of response appear to be critically relevant to flying qualities. Particularly important is the magnitude of the residue in each of the response variables of pitch, angle of attack, and speed change. In view of the fact that these residues are a direct function of the feedback configuration, this is an important area of flying qualities/FCS design interface that should receive concentrated attention in the near future.

Q. Berthe, Charles J; Chalk, Charles R and Sarrafian, Shahan, "Pitch Rate Flight Control Systems in the Flared Landing Task and Design Criteria Development", Calspan Report No. 7205-6, October 1984

The investigation using the TIFS was concerned with design criteria for pitch rate command systems as applied to the flared landing task. It used a generic transport (193,000lb gross) with static instability. Twenty seven configurations were tested, from 7 aerodynamic models and eight pitch axis FCS, with selected pre-filters and wash out filters. The report gives a detailed analysis of the generic aircraft model used.

Selected Conclusions.

1. Current integral-proportional pitch rate command FCS can provide excellent attitude control, i.e. pitch pointing. However, although good attitude control is a prerequisite for the flared landing task it is not sufficient to provide level 1 performance.

2. The pilot requires "surrogate" feedback cues to precisely control flight path in the landing flare. For conventional short period and phugoid dynamics he can use the following cues:

   * Initial acceleration at the pilot station.

   * Stick deflection and stick force are related to angle of attack and flight path.

   * Initial attitude response during short period transient reflects commanded angle of attack.

   * Longer term pitch rate and attitude indicates flight path rate and flight path angle.

   In the case of rate command attitude hold systems, the stick commands pitch rate and the control system holds pitch attitude when the stick command is zero. Stick deflection and pitch rate are nearly proportional but neither give very useful cues as to what the angle of attack and flight path are doing. This is because the control system causes two of the dynamic modes to be decoupled from the pitch rate and attitude response but not from the angle of attack or flight path responses. The augmented roots near $1/T_{\theta_1}$ and $1/T_{\theta_2}$ are cancelled in the pitch attitude transfer function but not in alpha or gamma. These dynamic modes are excited by pilot control actions and cause continuous variation of angle of attack, flight path and speed but not pitch attitude. Thus two primary cues normally used by the pilot (i.e. stick feel and pitch attitude) as "surrogates" for controlling flight path are reduced in value for this purpose because the control system decouples the pitch attitude from the dynamic responses of angle of attack, flight path angle and airspeed.

3. The most direct way to provide these cues and consequent level 1 landing performance is to utilize angle of attack and pitch rate feedback to achieve "conventional" short period and phugoid characteristics.

4. Classical predictive criteria i.e. bandwidth criteria, equivalent systems criteria, Neal-Smith criteria, etc., when based on pitch attitude do not provide adequate flying qualities predictions for the flared landing task.

R. Bailey, Randall E, "Experimental Investigation of the Short Period Response Requirements of MIL-F-8785C", Volumes I & II, Calspan Report No. 7205-9 (AFWAL-TR-86-3109), December 1985

The investigation considers changes to MIL-F-8785C requirements for SPPO responses and its requirements as a function of the parameter (n/α) for the lower limit. It also considered pilot location.

It looked at the use of $T_{\theta 2}$ as a specification parameter instead of (n/α) and suggests use of the Bandwidth criterion.

The study was constrained to up and away tasks and mainly military type aircraft. Although interesting it is of no great direct relevance to the present study.

S. Weingarten, Norman C, "An In-Flight Investigation of Various Longitudinal Flight Control Systems in the Space Shuttle Orbiter During Approach and Landing", Calspan Report No. 7263-1, December 1985

This report follows from report M in that this reports the implementation of the analysis of the former.

The Orbiter's approach and landing pitch flight control system is a tight rate command system which changes and holds attitude well without overshoot for sharp pulse type inputs. Flight path control is rather sluggish however.

The system is good for the initial steep approach where the astronauts just point it at a target. They report that they don't trust their motion and acceleration cues after spaceflight and therefore use their visual cues which are provided for well with the existing system. The system is not so good, however, for the final flare and touchdown where the sluggish flight path control can lead to a floating and ballooning tendency.

Several systems were evaluated, using the USAF NC-131H TIFS aircraft, including a blend of normal acceleration and pitch rate. The two non-astronaut evaluation pilots preferred this system, however the two astronauts preferred to use their pulsing piloting technique on the existing system.

It is also noted that whereas the non-astronaut evaluation pilots were not told which system they were assessing, a pre-condition of the astronauts participation was that they were so told. The degree of polarity between the opinions of the two different groups can be summarised by the inclusion in the report of a statement by Calspan Chief Test Pilot, Charles Berthe, to the effect that both groups were indeed partially correct.

The report contains a good description of the Space Shuttle Orbiter's aerodynamics and FCS design.

T. Weingarten, Norman C; Berthe, Charles J Jr; Rynaski, Edmund G and Sarrafian, Shahan K, "Flared Landing Approach Flying Qualities", Vols I & II, Calspan Report No. 7205-13, December 1986

The investigation concerning longitudinal flying qualities for the approach and landing tasks was performed using the USAF NC-131H TIFS. The purpose of the experiment was to generate a consistent set of data for:

1. determining what kind of commanded response the pilot prefers/requires in order to flare and land an airplane with precision, and
2. refining a time history criterion that took into account all the necessary variables and their characteristics that would accurately predict flying qualities.

The results of the first part of the study provides guidelines to the flight control system designer, using MIL-F-8785C as a guide, that yield the dynamic behaviour pilots prefer in flared landings. The results of the second part of the study provides the flying qualities engineer with a newly derived flying qualities predictive tool which appears to be highly accurate.

It makes the point that the MIL-SPEC short period requirements are for alpha responses.

An excellent report with pilot comment cards and raw data.

U. Bailey, Randall E; Knotts, Louis and Levison, "An Investigation of Time Delay During In-Flight and Ground-Based Simulation", Volumes I & II, Calspan Report No. 7205-16, August 1987

The investigation simulated four aircraft models (C-17, C-141, F-16 and C-21) using the NT-33A both in-flight and on the ground. The aircraft were chosen to represent a variety of sizes (C-17 and C-141 large, F-16 and C-21 small), and tasks (F-16 and C-17 represent demanding tasks, C-21 and C-141 benign tasks).

In flight the flying qualities degraded from level 1 to level 2 beyond 150 msec of total delay from pilot input to visual cue (and correspondingly 110 msec total equivalent delay between cockpit input and motion system response).

Beyond 150 msec flying qualities degraded at approximately 1.5 rating units for each 100 msec of added delay.

At highest delays (240 msec pure transport delay - experiment variable - gives 340 msec total HUD/Visual equivalent delay) PIOs were a major problem. All pilots tried different techniques to overcome PIOs, for example a tight grip on the controls in order to give sensitive small movements.

V. Chalk, Charles R, "Flying Qualities Review, Assessment and Recommendations for NASP", Calspan Report No. 7678-1, February 1989

The report goes into considerable detail of the application of the current criteria to the US National Aerospaceplane. In that respect it is similar to the current study being undertaken for civil aircraft, and contains a very useful list of references.

W. Ohmit, Eric E, "Final Report, Phase I MD-12 TIFS Simulation Program", Calspan Report No. 7738-13, July 1992

The specification of the MD-12 FCS is a three axis FBW control system to provide good flying qualities and wing load/gust alleviation of the reduced static stability aircraft.

The objectives of the study were to select a baseline longitudinal Stability and Control Augmentation System (SCAS) from three or four candidate systems which were developed during DAC ground simulation testing. The three control law configurations were alpha, theta and gamma command systems.

Conclusions.

1. Pilots disliked the uncommanded pitch activity of the gamma command control laws in turbulence.

2. The gamma command control laws have a significantly higher response to turbulence compared to theta and alpha command control systems - low frequency phugoid range.

3. Touchdown dispersions between the control law candidates were not significant.

4. Attitude command control law performance appears sensitive to piloting technique.

5. Pilot ratings did not reflect a clear preference for one law over another. (Turbulence levels for these tests were low).

It was also noted that a correctly functioning autothrottle is important to the task. (Problems with the initial implementation were overcome.)