Cranfield
UNIVERSITY

A piloted simulation investigation of several command concepts for transport aircraft in the approach and landing

E.Field

COA report No.9401
February 1994

College of Aeronautics
Cranfield University
Cranfield
Bedford MK43 0AL
England

College of Aeronautics Report No. 9401
February 1994

A piloted simulation investigation of several command concepts for transport aircraft in the approach and landing

Edmund Field

ISBN 1 871564 700

£10

Flight Dynamics Group
College of Aeronautics
Cranfield University
Cranfield, Bedford MK43 0AL
England

ACKNOWLEDGEMENTS

The investigation reported herein was performed under the terms and conditions of a Total Technology PhD programme sponsored by the Science and Engineering Research Council. The work was performed within the Flight Dynamics Group of the College of Aeronautics by Mr Edmund Field, under the supervision of Mr Michael Cook. Industrial collaboration for the programme is with the Avro International Aerospace division of British Aerospace, Woodford, Mr Michael Green providing the industrial supervision.

The assistance of Messrs. Lawrence Foster, Phillip Sheen and Jerry Downs of Avro International Aerospace in providing the aircraft model and implementing the configurations in the simulator is gratefully acknowledged, as is that of Mr John Allen of British Aerospace, Hatfield, who was responsible for the operation of the simulator.

The author would also like to express his appreciation to the evaluation pilots who participated in the investigation, Messrs. Roger Bailey, Les Evans, Mervyn Evans and D A Z James. Additionally Mr Roger Bailey for his assistance throughout the investigation, in particular in the development of the evaluation procedure.

CONTENTS

APPENDICES

FIGURES

TABLES

NOTATION

Abbreviations

agl	Above Ground Level
ASTRA	Advanced Systems Training Aircraft
CAP	Control Anticipation Parameter
CG	Centre of Gravity
CoA	College of Aeronautics
DBI	Distance Bearing Indicator
DEC	Digital Equipment Corporation
EAS	Equivalent AirSpeed
EFIS	Electronic Flight Instrumentation System
ETPS	Empire Test Pilot School
fps	Feet Per Second
ft	Feet
GPWS	Ground Proximity Warning System
Hz	Hertz
IAS	Indicated AirSpeed
ILS	Instrument Landing System
ITPS	International Test Pilot School
kts	Knots
lb	Pounds
LED	Light Emitting Diode
PAPI	Precision Approach Path Indicator
PIO	Pilot Induced Oscillation
PPI	Proportional Plus Integral
QNH	Local altimeter setting to give altitude above mean sea level
rad	Radians
RAE	Royal Aircraft Establishment/Royal Aerospace Establishment
RAF	Royal Air Force
RJ	Regional Jet
rpm	revolutions per minute
s	Second
TIFS	Total In-Flight Simulator
TPS	Test Pilot School
US	United States
USAF	United States Air Force

NOTATION

Symbols

A	Aircraft state matrix
B	Aircraft input matrix
$\bar{c}$	Mean aerodynamic chord
D_x	Transfer function denominator of variable x
g	Gravitational constant
I_y	Moment of inertia about the Y axis in pitch
$k_{\dot{\varepsilon}_q}$	Derivative of pitch rate error feedback gain
k_q	Pitch rate numerator constant
k_α	Angle of attack numerator constant
K	Feedback gain matrix
$\mathrm{K_c}$	Command gain
$\mathrm{K_{err}}$	Error feedback gain
$\mathrm{K_q}$	Pitch rate feedback gain
$\mathrm{K_u}$	Forward speed feedback gain
K_α	Angle of attack feedback gain
K_θ	Pitch attitude feedback gain
l_p	Pilot moment arm about the centre of gravity
M	Aircraft mass matrix
M_q	Dimensional stability derivative of pitching moment due to change in pitch rate
M_α	Dimensional stability derivative of pitching moment due to change in angle of attack
$M_{\dot{\alpha}}$	Dimensional stability derivative of pitching moment to change in angle of attack rate
M_η	Dimensional stability derivative of pitching moment due to change in elevator position
m	Feedforward gain
m	Mass
N1	Engine fan speed in % rpm
N2	Engine core speed in % rpm
N_x	Transfer function numerator of variable x
n/α	Acceleration sensitivity
$n_{z_{cg}}$	Normal load factor at the centre of gravity (g's)
n_{z_p}	Normal load factor at the pilot station (g's)
q	Pitch rate
$\dot{q}$	Pitch acceleration
q_d	Demanded pitch rate
s	Laplace operator
$1/T_{\theta_1}$	Low frequency zero in pitch rate transfer function (sec^{-1})
$1/T_{\theta_2}$	High frequency zero in pitch rate transfer function (sec^{-1})

U_e	Steady state forward velocity
u	Perturbation in forward velocity
V	Airspeed
Z_q	Dimensional stability derivative of normal force due to change in pitch
Z_α	Dimensional stability derivative of normal force due to change in angle of attack
$Z_{\dot{\alpha}}$	Dimensional stability derivative of normal force due to change in angle of attack rate
Z_η	Dimensional stability derivative of normal force due to change in elevator position
z_i	Zero of PPI controller feedforward path
α	Angle of attack
$\dot{\alpha}$	Angle of attack rate
ε	Error
$\dot{\varepsilon}$	Error rate
γ	Flight path
γ_{cg}	Flight path at the centre of gravity
$\dot{\gamma}_{cg}$	Flight path at the centre of gravity rate
$\dot{\gamma}_{cg_d}$	Demanded flight path at the centre of gravity rate
γ_p	Flight path at the pilot station
$\dot{\gamma}_p$	Flight path at the pilot station rate
$\dot{\gamma}_{p_d}$	Demanded flight path at the pilot station rate
η	Elevator deflection
θ	Pitch attitude
$\dot{\theta}$	Pitch rate for small perturbations (q)
τ_r	Roll subsidence mode time constant (seconds)
ω	Natural frequency (rad/sec)
ω_α	Natural frequency of angle of attack numerator complex term (rad/sec)
ω_{dr}	Natural frequency of Dutch roll mode
ω_{ph}	Natural frequency of phugoid mode (rad/sec)
ω_{sp}	Natural frequency of short period mode (rad/sec)
ζ	Damping ratio
ζ_α	Damping ratio of angle of attack numerator complex term
ζ_{dr}	Damping ratio of Dutch roll mode
ζ_{ph}	Damping ratio of phugoid mode
ζ_{sp}	Damping ratio of short period mode

1. INTRODUCTION

With the introduction of modern fly-by-wire aircraft, the response of an aircraft to a pilot's input can be augmented to something other than that for a conventional aircraft, with the resultant benefits and problems. The issue of what commanded response a pilot desires has received considerable attention, however no clear conclusions have yet emerged.

The requirements for up and away flight and for the flare and landing seem to be different. Away from the ground rate command systems such as pitch rate and flight path rate seem to be well received for their low pilot workload associated with the control of flight path. However in the flare and touchdown these systems exhibit unnatural floating tendencies, requiring the pilot to push forward on the stick to land the aircraft. As a result most fly-by-wire aircraft incorporate separate up and away control laws and flare laws.

This investigation is designed to consolidate on the work achieved by many organisations over the past ten years and concentrate on pilots' preferences for the final stages of the approach and into the flare and touchdown.

Twenty nine different flight control law configurations were designed for a regional sized aircraft. These configurations concentrated on several different command philosophies designed to investigate the pilots' preferred command parameter and covered three different centre of gravity locations. These configurations were then implemented on the fixed base engineering simulator at British Aerospace Regional Aircraft, Hatfield, and evaluated by four test pilots.

1.1 Previous Work

Many investigations have been undertaken concerning what commanded response transport aircraft pilots prefer. These investigations have tended to be either of a general research nature or concern the application of specific flight control law designs, generally in support of a specific aircraft development programme by the manufacturer.

The Arvin/Calspan Corporation's Flight Research Department (Calspan) have undertaken many in flight simulation programmes both of a research nature and for the manufacturers. Investigations such as those reported in references 1 to 3 fall into the former category and have been used extensively in the design of this investigation. These studies make use of an inherently unstable aircraft and use the feedback of the command parameter to stabilise the aircraft, usually concentrating on angle of attack and pitch rate. These studies have concluded that pilots want pitch attitude to be usable in determining the aircraft's flight path. For both the angle of attack and pitch rate command systems considered it was found that pilots prefer those configurations whose angle of attack response was "well behaved" as defined by MIL-F-8785C, reference 4. More recently other parameters, especially flight path, have started to receive greater attention.

Other Calspan in-flight simulation investigations have been performed for various aircraft manufacturers, particularly Boeing and McDonnell Douglas. However, much of this work is unpublished and is limited to the application of a small number of control law concepts to a specific aircraft model. As a result the readover of the results, where available, from one study to another is limited.

Airbus produced the first commercial transport aircraft with a full authority digital fly-by-wire flight control system. The A320 first flew in 1987 and entered airline service in 1988. In up and away flight the aircraft utilises a C* flight control law which exhibits neutral static stability and therefore no need for the pilot to trim. The drawback of this system is that there is no tactile feedback to the pilot of airspeed, therefore requiring considerable low speed envelope protection. Configuration changes produce flight path deviations which must be corrected by the pilot, however no trim changes are required as in conventional aircraft.

In the landing flare the pitch rate element of the C* control law dominates, leading to a tendency to over rotate resulting in an unnatural tendency to have to push forward on the stick to land the aircraft, apparent to the pilots as non-monotonic stick forces in the flare. As a result Airbus implemented a separate flare law on the A320 based on pitch attitude command. At a height of 50 feet the aircraft's pitch attitude is memorised, the reference attitude. Below 30 feet the reference attitude is progressively reduced by 2° nose down over a period of 8 seconds. This causes the aircraft to pitch nose down by the 2° and so the pilot must apply a gentle positive back force on the stick to flare the aircraft, reference 5.

The flare law of the A320 gives a slightly unconventional feel in the flare and so Airbus developed an alternative for the A330/340. In these aircraft below 50 feet ground speed is fed back in addition to the C* loop. The result of this is that as the speed of the aircraft reduces in the flare the speed loop causes the nose to lower, more like a conventional aircraft. In order to stop the nose lowering the pilot must apply a continual back force to the stick, thus restoring monotonic stick forces and making the aircraft feel more conventional in the flare.

Recent work by Boeing has been in support of two aircraft programmes, firstly the 7J7 and secondly the 777. The basis of the proposed 7J7 flight control law was a flight path angle rate command system which was the subject of a ground simulation programme as well as an extensive in-flight simulation programme utilising the USAF TIFS, references 6 and 7. Up and away the pilot commanded a selected flight path angle on his display and the aircraft then pitched and adjusted power accordingly. This system allowed "pilot in the loop" operation but required very low pilot workload. Additionally the pilot could fine tune the flight path using a vernier command thumb switch.

It was found that the uncommanded motions of this system were quite natural and that ride qualities in turbulence were excellent. No pilot inputs were required to fight the turbulence, and no trim inputs were required to compensate for flap or gear deployment.

Due to the problems of non-monotonic stick forces in the flare with rate command systems two flare laws were considered. Firstly a delta-gamma mode which "locked on" to a reference flight path angle during pre-flare, consequently requiring a back force on the controller to hold a flight path higher than the reference value, and secondly a delta-theta mode which "locked on" to a reference pitch attitude during the pre-flare requiring a back force on the controller to hold a pitch attitude greater than the reference value. Originally the reference value was taken as that when the aircraft passed through 100 feet radio altitude, however was later changed to that at 30 feet.

Comments from airline pilots who flew the ground simulator were very positive towards the flight control laws. The in-flight simulations showed the flare and touchdown to be the most demanding task, and somewhat more demanding than in the ground simulator. It was concluded that further flare law development was required.

More recently Boeing's work has been concentrated on the 777, reference 8. Following their earlier work they developed a different system for their first commercial transport to incorporate a digital fly-by-wire flight control system. The C*U flight control law is a development of the C* control law originally developed by Boeing in the 1960's, reference 9. It utilises the C* flight path control with a U (airspeed) feedback to give speed stability and column forces to the pilot as in a conventional aircraft.

The aircraft is trimmed to a speed and any deviation from this speed will cause a trim change. The backfeed on the controller will produce a force of approximately 12 lbs for a speed change of 40 kts, if not trimmed out, reference 10. Configuration and power changes, however, do not alter the flight path and require no trim change. In addition to the conventional C*U control law Boeing investigated several flare laws, including a linear pitch down command schedule based on radio height.

In order to evaluate the 777 flight control laws Boeing modified a 757-200 to emulate the 777 fly-by-wire control laws, reference 8. During the initial test flights the control laws were fine tuned. Subsequently Boeing invited representatives from several airlines to fly the 757 emulating the 777, references 10 and 11. The responses from these pilots were positive, they reported that tendency to float in the flare was minimised and that it felt more natural than the A320. Flare with the conventional C*U control law and no additional flare law was also easily managed.

The Douglas Aircraft Company used the USAF TIFS in support of its MD-12 development, reference 12. Their investigation was of a more general nature than those of Boeing, considering several control concepts, namely angle of attack, pitch attitude, pitch rate and flight path rate. In this investigation the flight path rate control law was not as well received as in the Boeing 7J7 simulations, with pilots disliking the uncommanded pitch activity in turbulence.

There was no clear preference for one system over the others, touchdown dispersions between the control laws were not significant, however it was noted that turbulence levels in these tests was low. It was also noted that performance of the pitch attitude command system appeared sensitive to pilot technique.

Further research by Douglas into large aircraft flying qualities, reference 13, has been of a more general nature than aircraft specific control law development as previously discussed. Using a generic advanced technology large transport aircraft of approximately one million pounds weight they considered both angle of attack and pitch attitude command systems. The investigation covered several values of Control Anticipation Parameter (CAP) for each command system.

Results from the angle of attack command configurations suggest that the lower level 1 CAP boundary could be moved up slightly for transport aircraft, possibly to a value of 0.5. The lower level 2 boundary appears to be acceptable at its current value. The initial study of the pitch attitude command system was inconclusive with further analysis planned to better quantify the floating tendencies in the flare.

Fokker, in 1992, applied three pitch control laws to a fly-by-wire controlled Fokker 100 using a fixed base simulator, reference 14. The first system, the simplest of the three, was pitch rate command implemented with only pitch rate feedback. The second, an advanced design compared to the first, was flight path vector command and was based on the system used in the Boeing 7J7 simulations. This system utilised a special symbology on the primary flight display to show the actual flight path that the pilot was commanding. The final system was C* command and was based on the A320 control laws.

The most favourable pilot comments were given to the flight path command concept. Pilots particularly liked the constant awareness of the aircraft's flight path vector and the ability of controlling it directly. Absence of flight path deviations in turbulence and with configuration changes was also liked. However the drawback of this flight path stability was found to be that the pilots did not have to interfere for such extended periods of time that they were hardly aware the aircraft was still being controlled manually. This problem was not found with the pitch rate and C* concepts. At the other extreme the complete absence of speed stability, as in the rate command concept, appeared to be unacceptable.

1.2 Aims of this Investigation

The main aim of this investigation was to determine what commanded response variable pilots prefer. While this was also a major aim of many of the investigations discussed above they usually considered a few different concepts, often advanced, applied to a specific aircraft. Few studies have systematically considered a wide variety of different concepts on one aircraft. The closest to this is probably the work done by Douglas, reference 12, in support of the MD-12 programme which considered four different command parameters.

Alternatively the Calspan studies of references 1 - 3 used a generically unstable aircraft as the host for the control laws. With a generically unstable aircraft there is therefore a need for feedback in order to stabilise the aircraft. This feedback was the basis for the control law. However, current requirements, which are unlikely to be relaxed in the short or medium term, are for the unaugmented aircraft to have a degree of inherent stability, so that it will degrade to a flyable aircraft in the event of a flight control system failure. Therefore for the foreseeable future the baseline unaugmented aircraft will likely be inherently stable. As a result any command and stability augmentation system is unlikely to greatly alter the modal response of the aircraft. It is therefore more likely that a combination of feedback parameters will be required to produce the desired response rather than just one feedback quantity, especially when exact pole placement is required.

The aim of the present study was to consolidate on the previous work done by many others in determining what commanded response pilots prefer. In this way many different control law concepts were applied to one aircraft model, thus allowing a clearer comparison of one concept against another. Similar to the work by McDonnell Douglas and Calspan the control laws considered centred around command of the basic aircraft longitudinal parameters, namely angle of attack, pitch attitude and flight path.

The aircraft model used for the study was that of a generic twin engined regional jet with a landing weight of 90,000 lb. By considering an aircraft at the lower end of the weight range, compared to the near 1,000,000 lb MD-12, problems of delays due to inertia and structural flexibility are minimised, such that the pilot is able to concentrate his attention on the control law characteristics themselves.

The basic dynamics of the host aircraft, the short period and phugoid modal properties, were retained, where applicable, in the control law configurations. The control laws use command augmentation to produce the desired short and long term responses. In this way the configurations are kept close to the unaugmented host aircraft, in consideration of a flight control failure.

This investigation is also the first attempt during the current research programme at designing, implementing and evaluating control laws on an engineering simulator. The establishment of this process and identification of improvements for future studies must therefore be considered primary goals of this investigation.

2. CONTROL LAW DESIGNS

2.1 Philosophy Behind the Designs

A conventional aircraft is angle of attack command. It is often argued that it is pitch rate command, and for that matter many other parameters as well, however this is only true for the short term response. If the longer term dynamics are considered it is apparent that in the steady state a step input to the elevator will produce a near step change in angle of attack, however the other parameters do not give a constant positive steady state value. Figure 1 shows the response to a step input to elevator of the baseline unaugmented aircraft used in this investigation. It is clear from these responses that in the long term the response that most resembles the input is the angle of attack. All the other responses exhibit a longer term non steady state response, the phugoid mode. These responses will ultimately go to zero as long as the phugoid is damped. The angle of attack response however shows very little phugoid residue in its response, or exhibits minimal phugoid visibility.

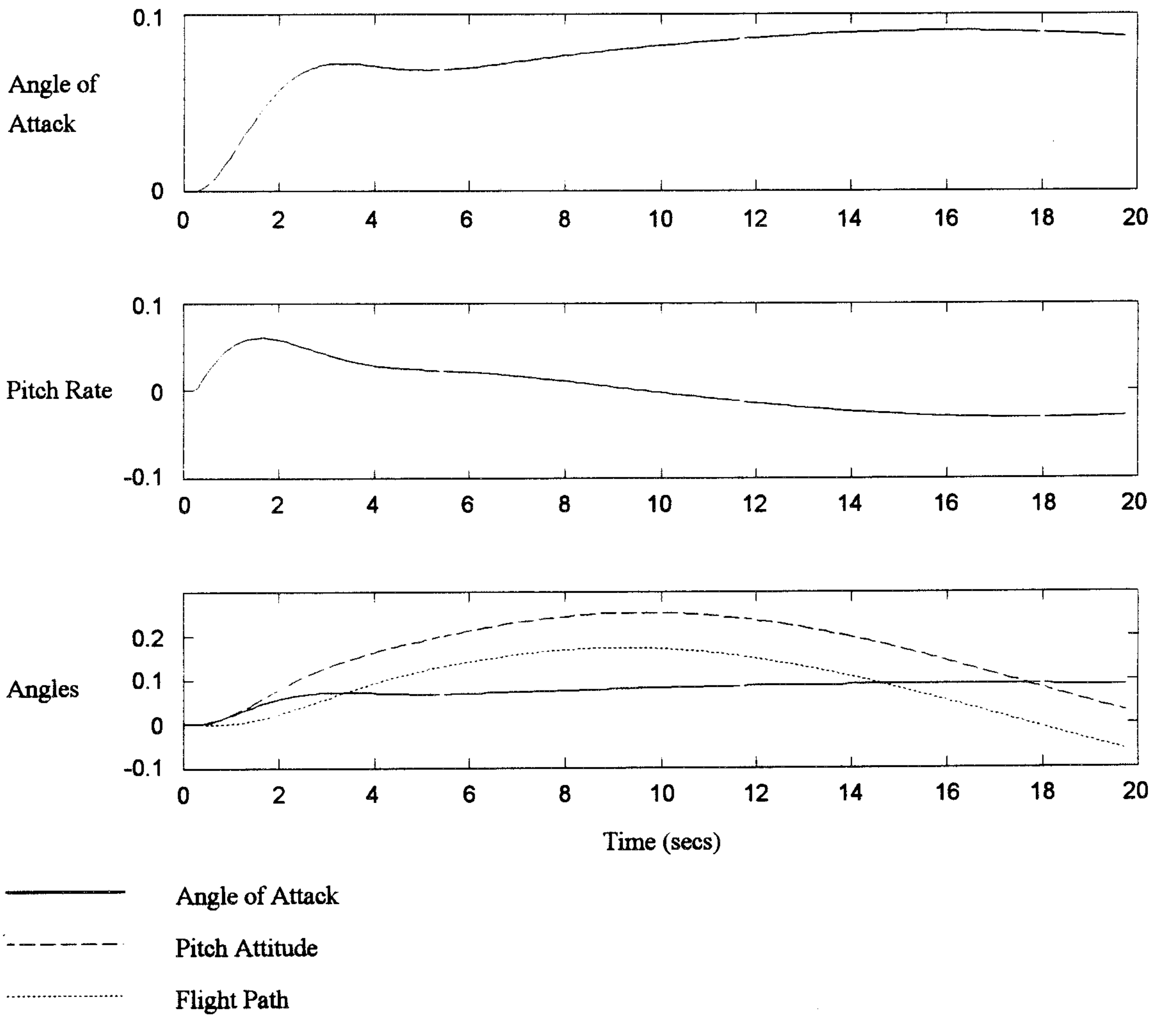


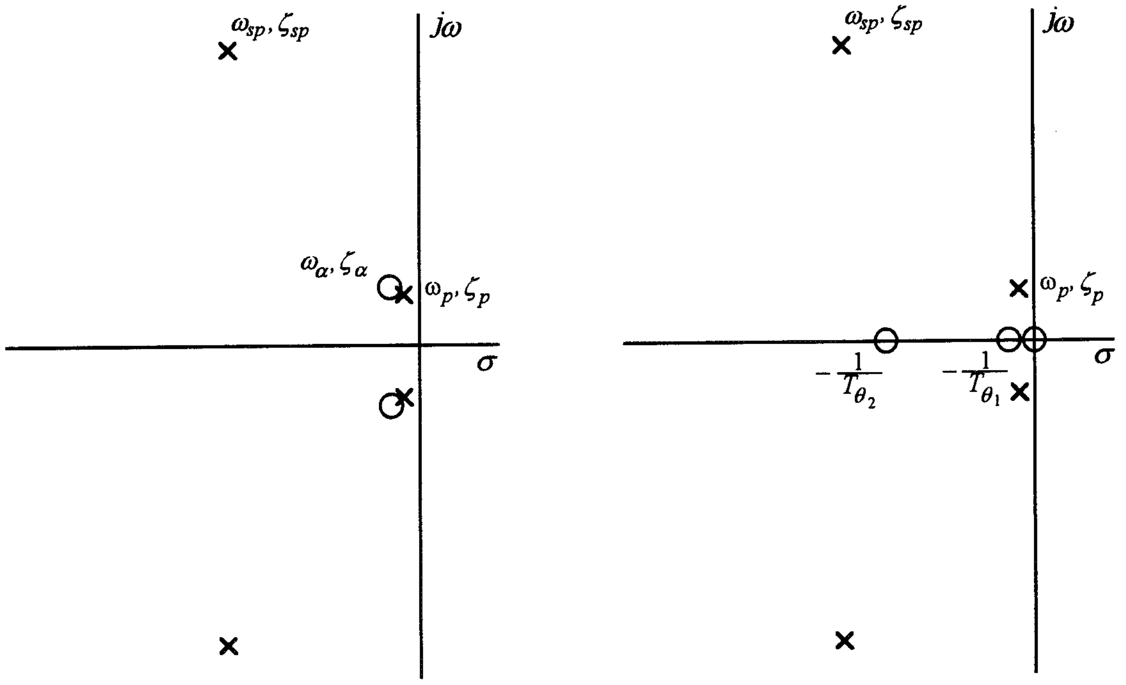
Figure 1 Conventional Aircraft Response to a Step Input to Elevator

The transfer functions of angle of attack and pitch rate for a conventional aircraft are given by:

$$\frac{\alpha(s)}{\eta(s)}=\frac{k_\alpha\left(s^2+2\zeta\omega_\alpha+\omega_\alpha^2\right)}{\left(s^2+2\zeta\omega_{sp}+\omega_{sp}^2\right)\left(s^2+2\zeta\omega_p+\omega_p^2\right)}$$

$$\frac{q(s)}{\eta(s)}=\frac{k_q s\left(s+1/T_{\theta_1}\right)\left(s+1/T_{\theta_2}\right)}{\left(s^2+2\zeta\omega_{sp}+\omega_{sp}^2\right)\left(s^2+2\zeta\omega_p+\omega_p^2\right)}$$

Figure 2 shows these schematically in pole-zero plots. Clearly the short term response in angle of attack is dominated by the two short period poles. In the longer term the phugoid poles are almost cancelled by the complex angle of attack zeros, thus leading to the minimal residue in the angle of attack phugoid. In the pitch rate response the zero at $(s+1/T_{\theta_2})$ is of similar frequency to the short period poles resulting in a faster initial pitch rate response with considerably greater overshoot than that for the angle of attack response, as can clearly be seen in figure 1. In the longer term there is no cancellation of the phugoid poles and so a phugoid response is clearly visible in the pitch rate response of figure 1.



Angle of Attack pole-zero pattern

Pitch Rate pole-zero pattern

Figure 2 Conventional Aircraft Pole-Zero Plots

The responses of figure 1 can be compared to those of figure 3. These represent the response of a true angle of attack command system for the same aircraft. This was obtained using full state feedback to place the phugoid poles at the angle of attack numerator zeros, thus ensuring complete pole/zero cancellation and so no phugoid residue in the angle of attack response, figure 4. The similarity between the responses of figures 1 and 3 is apparent.

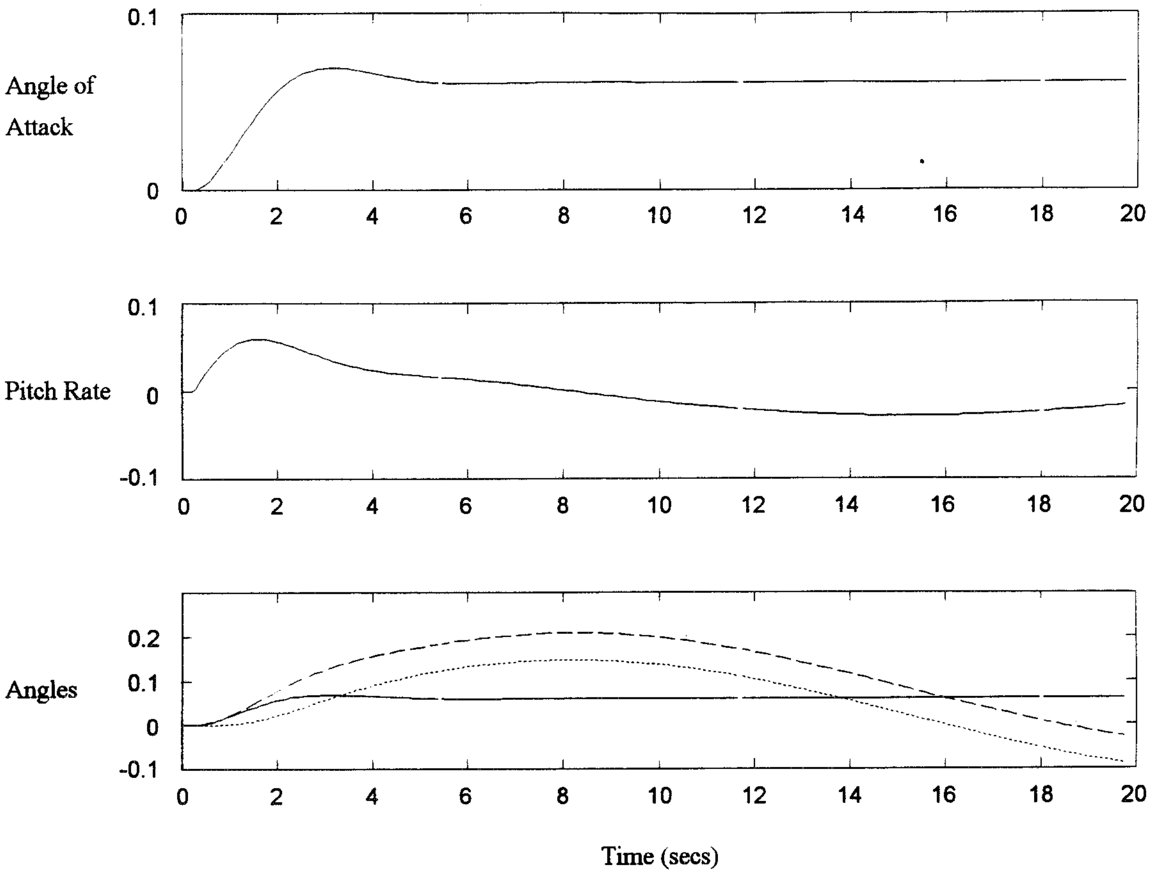
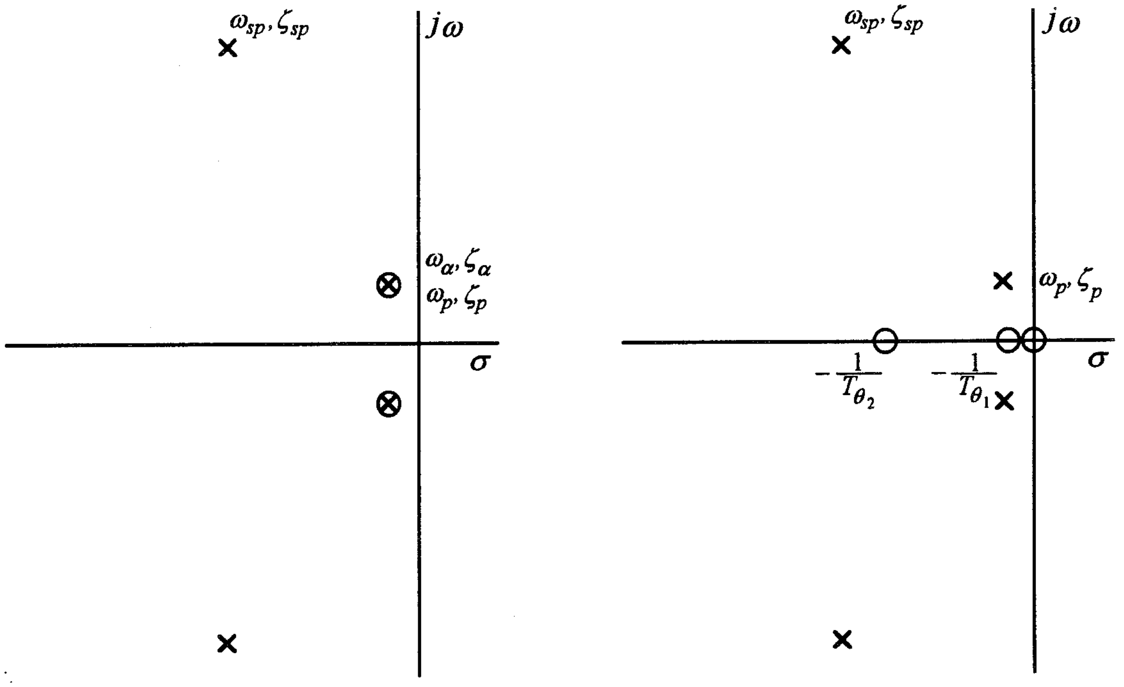


Figure 3 Angle of Attack Command System Responses



Angle of Attack pole-zero pattern

Pitch Rate pole-zero pattern

Figure 4 Angle of Attack Command System Pole-Zero Plots

It is for this reason that conventional aircraft are considered angle of attack command, since a pilot's input to the stick will produce approximately a new steady state angle of attack, the pitch rate however will not be steady state. If the initial response to a pilot's input is considered then it is true that the pilot is causing a change in the pitch rate of the aircraft, but he is also causing a change in the flight path, flight path rate, pitch attitude and many other parameters. This does not mean that he has direct control of these parameters, only that these parameters change when the pilot makes an input to the stick. The short term response can also be considered the manoeuvring response, however the pilot must be able to accurately and predictably stop the manoeuvre and for that he requires direct control over the longer term response.

Clearly in a conventional aircraft as the pilot moves the stick he is directly commanding the angle of attack of the aircraft in the longer term. Considering the basic relationship between angle of attack, pitch attitude and flight path:

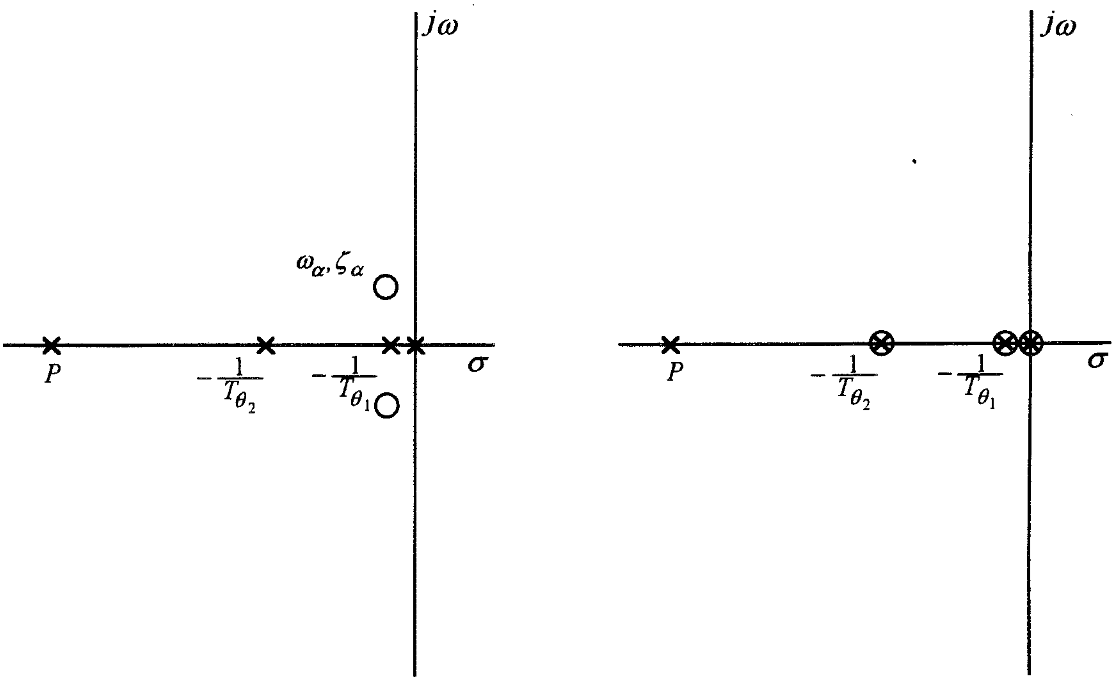
$$\gamma_{cg} = \theta - \alpha \tag{1}$$

if in the long term there is minimal change in the angle of attack response then any change in the pitch attitude will be mirrored in the flight path response. Figures 1 & 3 show the similarity between the pitch attitude and flight path responses. In this way a pilot is able to predict the flight path of the aircraft from observation of the pitch attitude. If however the angle of attack response exhibits an appreciable phugoid residue then the above argument does not hold.

A popular flight control system design is that of pitch rate command. As a feedback quantity pitch rate is easily measured and so easily implemented. The main advantage of a pitch rate command system comes in manoeuvring and holding an accurate pitch attitude. To raise or lower the nose of the aircraft the pilot only needs to apply a force and as long as the force is constant the aircraft will pitch at a constant rate - nice for manoeuvring. As soon as the pilot releases the stick it will return to the null position and so command a zero pitch rate, in other words hold the pitch attitude, due to the rate command denominator pole at $(s = 0)$. This system is therefore desirable for fast manoeuvring and accurate attitude control, providing a stable platform for tasks such as stores release.

A pitch rate command system may be implemented using pole/zero cancellation in the same way as the angle of attack command system described above. Figure 5 shows the pitch rate and angle of attack pole-zero plots for the basic aircraft with a pitch rate command system. The poles of the aircraft are placed so as to cancel the pitch rate numerators at $(s+1/T_{\theta_1})$, $(s+1/T_{\theta_2})$, the origin $(s+0)$ and to introduce a pole at $(s+P)$, where P is chosen to be of similar frequency to the short period mode. The result is an equivalent first order step response in pitch rate dominated by the pole at $(s+P)$, however the angle of attack response is no longer constant in the steady state, figure 6.

The pitch rate command system also produces a sluggish angle of attack response which leads to a tendency for pilots to over control in the flare. The correction for this is for the pilot to release the back pressure or even push forward on the stick, leading to complaints of non-monotonic stick forces. Additionally the response of the flight path no



Angle of Attack pole-zero pattern

Pitch Rate pole-zero pattern

Figure 5 Pitch Rate Command System Pole-Zero Plots

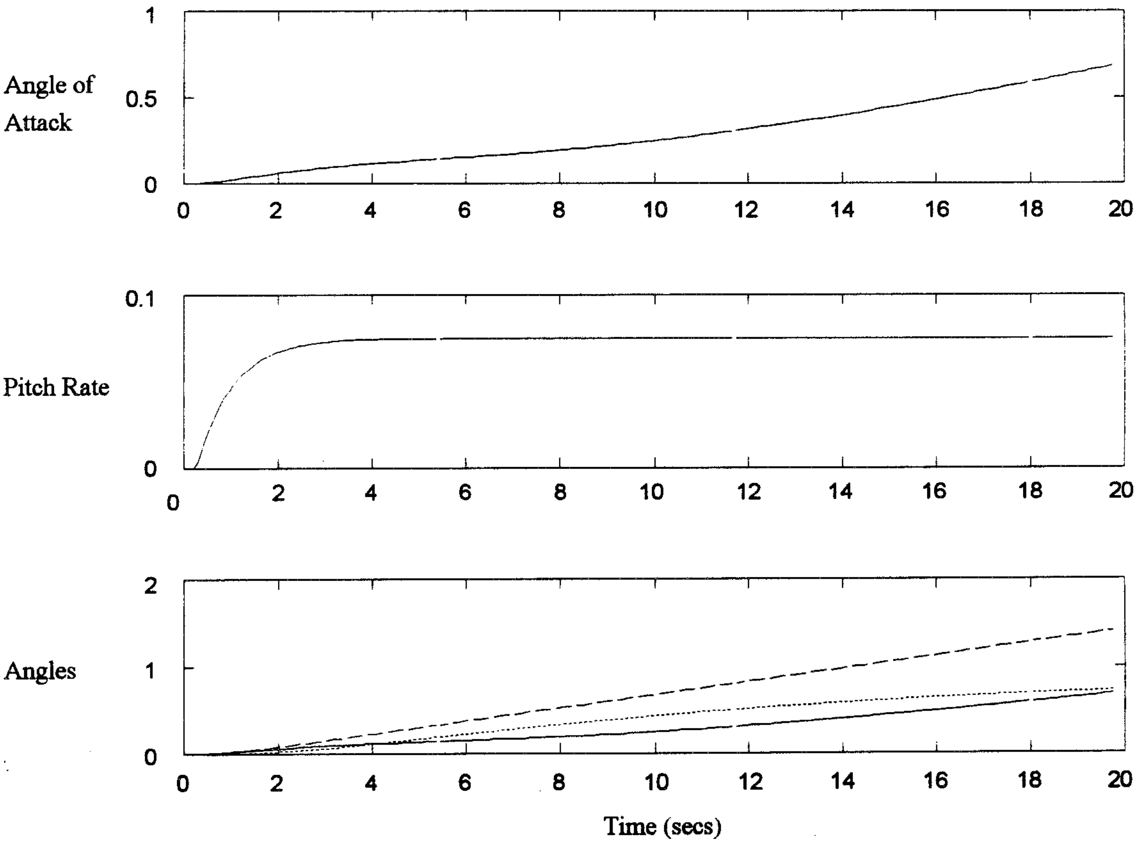


Figure 6 Pitch Rate Command Responses

longer accurately mirrors that of the pitch attitude, and so the pilot is no longer able to judge the flight path from observation of the pitch attitude. For dog fighting and stores release this is unlikely to be a major drawback for the pilot, however for accurate flight path control in the final stages of the approach and through the flare and touchdown this becomes critical.

To investigate what commanded response pilots prefer in the approach and landing it is necessary to understand the task they are performing. The task is to bring the aircraft into controlled contact with the runway. This implies accurate control of airspeed, flight path and attitude. If the combination of these is incorrect the pilot is unlikely to pull off a smooth landing. If the airspeed is slow the aircraft may land heavily or, in the extreme, stall, if fast the aircraft may float and use up considerable runway length. If the flight path is too steep the aircraft will make heavy contact with the ground, and if too shallow possibly no contact, at best floating some way down the runway. If the attitude is too great, nose up, there is a risk of scraping the tail, and if too low, nose down, the aircraft may land on its nose gear, both likely to interfere with the airline's scheduling!

Once visual, the pilot judges the aircraft's flight path using external cues. Sink rate is important. However, it can be difficult to judge at night. Generally the pilot should arrive at the threshold at the target speed, attitude and height. Between that point and the imperceptible touchdown he must select idle thrust and flare the aircraft. Closing the throttles will give a limited time to remain airborne before the speed reduces to an extent that the smooth landing will no longer be possible. Therefore the pilot must flare the aircraft enough so as to gradually and smoothly reduce its rate of descent to inches per second at touchdown, but not so much that the aircraft floats. Therefore accurate flight path control is critical, but so is the prediction of flight path.

Thus control of both pitch attitude and flight path is critical to the landing task. As discussed above an angle of attack command system will produce a flight path response that mirrors that of the pitch attitude, aiding in the control of flight path through the observation of pitch attitude. It is therefore apparent that control laws based upon the direct control of angle of attack, pitch attitude and flight path all have their benefits, as will those based upon their rates with their associated angle hold capability.

This investigation considers control laws commanding angle of attack, pitch attitude and flight path, the "angle controllers" and all of their rates, the "rate controllers". Angle of attack and pitch rate are the two natural aircraft states of constant speed aerodynamic flight, the other parameters can all be directly derived from these two. These are therefore the basic aircraft parameters that the pilot of a conventional aircraft either has control of implicitly, or that he is trying to control, as opposed to the synthesised parameters such as C*.

It is well recognised that rate command systems can give excellent flying qualities up and away, however show deficiencies in the flare. The Airbus A320 uses a variation of attitude control in the flare, the Boeing 7J7 considered both attitude and flight path control in the flare. This investigation also considers these concepts, however does not mix one concept in the approach with another in the flare, but considers each independently, thus identifying the relative benefits of each concept in each flight phase. This is compatible with the generic research nature of this investigation, designed to determine the pilot desired aircraft response, rather than considering the design of control laws for application to a particular aircraft.

2.2 Design Methods

Two sets of control law configurations were considered in this investigation, designated sets P and I. Set P configurations were designed using pole/zero cancellation while the set I configurations incorporate proportional plus integral controllers. All configurations were designed for a constant speed, reflected both in the following design processes and the evaluation procedure.

2.2.1 Set P Configurations

The set P control laws form the majority of the configurations. They cover angle of attack, pitch attitude, flight path angle and each of their rates. In fact there are two different flight path angle and rate configurations. The first is flight path measured at the centre of gravity and the second is flight path at the pilot station. The purpose of considering both systems was to identify the problems caused in flight path control when measured at a distance from the pilot.

Equation 1 gave the relationship between flight path measured at the centre of gravity, pitch attitude and angle of attack:

$$\gamma_{cg} = \theta - \alpha \tag{1}$$

Flight path rate measured at the centre of gravity is given by:

$$\dot{\gamma}_{cg} = \dot{\theta} - \dot{\alpha} \tag{2}$$

or:

$$\dot{\gamma}_{cg} = q - \dot{\alpha} \tag{3}$$

Normal load factor at the centre of gravity is given by:

$$n_{z_{cg}} = -\frac{V}{g}(\dot{\alpha} - q) \tag{4}$$

Thus:

$$n_{z_{cg}} = \frac{V}{g}\dot{\gamma}_{cg} \tag{5}$$

or:

$$\dot{\gamma}_{cg} = \frac{g}{V} n_{z_{cg}} \tag{6}$$

If equation 6 is a true relationship between flight path rate and normal load factor at the centre of gravity, then the following expression may be assumed for flight path rate and normal load factor at the pilot station.

$$\dot{\gamma}_p = \frac{g}{V} n_{z_p} \tag{7}$$

since

$$n_{z_p} = -\frac{V}{g}\left(\dot{\alpha} - q - \frac{l_p}{V}\dot{q}\right) \tag{8}$$

$$\dot{\gamma}_p = -\left(\dot{\alpha} - q - \frac{l_p}{V}\dot{q}\right) \tag{9}$$

and

$$\dot{\gamma}_p = \dot{\gamma}_{cg} + \frac{l_p}{V}\dot{q} \tag{10}$$

Given the numerators for angle of attack and pitch rate, those for angle of attack rate and pitch attitude may easily be calculated. Flight path and flight path rate at the centre of gravity are given by equations 1 and 3 respectively, while flight path rate at the pilot station is derived from equation 10, the integral of which will give the flight path at the pilot station. Therefore knowledge of the two natural states of constant speed aerodynamic flight, the pilot moment arm and the airspeed will give all the desired command parameter numerators.

From equations 6 and 7 it can be seen that a direct relationship exists between flight path rate and normal load factor since in the small perturbation approximation the airspeed and acceleration due to gravity are constant. Therefore any control law based upon pole/zero cancellation for flight path rate will also produce a normal load factor command system. Furthermore a normal load factor, or acceleration, command system, as is C* in up and away flight, will exhibit rate command like characteristics.

The control laws were designed using the approach of Weingarten et al., reference 3. As outlined in section 2.1 by placing the poles of the denominator to cancel the zeros of the appropriate numerator the desired aircraft response can be achieved. The aircraft states used in this investigation were defined as u, α, q and θ and fully describe the dynamics of the aircraft. Feedback of these four states was used to define the four aircraft poles which describe the short and long term response of the aircraft.

As further described in reference 3, by separating the short and long term responses it is possible to test whether the longer term response, or phugoid, is important to the pilot. By placement of the appropriate poles a hybrid control law of different short and long term responses can be designed. In this way the short term poles may be placed to cancel the pitch rate zero at $(s+1/T_{\theta_2})$ and to introduce a pole at $(s+P)$, while the long term poles may be placed to cancel the angle of attack zeros, thus producing a pitch rate command system in the short term, and an angle of attack command system in the long term. The same process may be used to design other hybrid command systems.

The pole placement technique to give pole/zero cancellation, as used in this investigation, does not produce robust control laws. These control laws can be sensitive to inexact pole/zero cancellation resulting from inaccurate pole placement due to modelling errors. The gains are also only correct for one particular speed, altitude and aircraft configuration. The control law designs of this investigation are not proposed for application in actual aircraft, they are purely relevant to the research nature of this investigation. Having identified pilots' desired aircraft response more robust control law designs can then be developed to give these desired characteristics.

2.2.2 Set I Configurations

There were several reasons for considering the proportional plus integral controllers. Firstly, proportional plus integral controllers tend to produce a crisper response than those of pure pole/zero cancellation, and also good longer term angle hold because of the integral loop driving the error signal to zero.

Secondly, the rate command control laws produced using pole/zero cancellation resulted in an equivalent first order system, thus showing no overshoot in the commanded response, and so a slower initial response in the commanded rate's associated angle. Because a basic proportional plus integral controller can restore the second order like response it can therefore produce an overshoot in the rate command control laws, thus giving a quicker initial response. It will therefore also speed the initial angle of attack response which is sluggish with the designs using simple pole/zero cancellation.

Additionally, proportional plus integral controllers are common in aircraft flight control systems due to their accurate control of the commanded parameter, and so their inclusion in this investigation seemed appropriate.

The third reason for including proportional plus integral controllers comes from the suggestion that as the static stability of an aircraft is reduced the problems of prediction of flight path from observation of pitch attitude becomes harder for rate command control laws, reference 15. As a result three different centre of gravity locations were considered for the pitch rate command system, forward, mid and aft. The mid CG location was used as the datum loading case with the fore and aft cases being limited in the number of configurations, concentrating upon the effect discussed above. The additional fore and aft cases also allowed additional testing of selected pole/zero cancellation configurations.

Proportional plus integral controllers were therefore designed for the pitch rate and both flight path rate command systems for the mid CG loading case, as well as the pitch rate command systems for all three CG locations.

2.3 Basic Aircraft Description

The aircraft model used for the investigation was a generic regional transport powered by two turbofan engines underslung from the aircraft's low wing.

Three loading cases were considered; the datum mid CG, case 8, a forward CG, case 7 and an aft CG, case 9. Cases 7 and 9 represent the forward and aft limits, respectively, for landing. The evaluation landing weight of 90,000 lb was the same for all loading cases, as was the airspeed of 126 kts EAS/IAS.

The following sections describe the basic aircraft for the three loading cases. The following short hand notation is used to describe the transfer functions:

$$N = k\,(a)\,[\zeta, \omega]$$

where: k: gain
(a): $(s+a)$
$[\zeta, \omega]$: $[s^2 + 2\zeta\omega s + \omega^2]$

2.3.1 Aircraft Description - Case 7

$\zeta_{sp} = 0.51$ $\omega_{sp} = 1.18$ rad/s $\zeta_{ph} = 0.038$ $\omega_{ph} = 0.191$ rad/s
$1/T_{\theta_2} = 0.53$ $l_p = 40.22$ ft CG = 13.5 % $\bar{c}$

Denominator: [0.51, 1.18] [0.038, 0.191]

N_α: -0.049 (18.5) [0.077, 0.211]
N_θ: -0.890 (0.084) (0.53)
N_q: -0.890 (0) (0.084) (0.53)
$N_{\gamma_{cg}}$: 0.049 (3.45) (-0.0026) (-3.01)
N_{γ_p}: -0.119 (-0.0026) [0.16, 2.10]

The time history responses, for a step input to the stick, for the unaugmented case 7 model are given in appendix A.

2.3.2 Aircraft Description - Case 8

$\zeta_{sp} = 0.54$ $\omega_{sp} = 1.28$ rad/s $\zeta_{ph} = 0.047$ $\omega_{ph} = 0.188$ rad/s
$1/T_{\theta_2} = 0.54$ $l_p = 41.28$ ft CG = 21.9 % $\bar{c}$

Denominator: [0.54, 1.28] [0.047, 0.188]

N_α: -0.049 (25.3) [0.079, 0.211]
N_θ: -1.22 (0.083) (0.54)
N_q: -1.22 (0) (0.083) (0.54)
$N_{\gamma_{cg}}$: 0.049 (4.11) (-0.0019) (-3.52)
N_{γ_p}: -0.188 (-0.0019) [0.16, 1.96]

The time history responses, for a step input to the stick, for the unaugmented case 8 model are given in appendix A.

2.3.3 Aircraft Description - Case 9

$\zeta_{sp} = 0.65$ $\omega_{sp} = 0.978$ rad/s $\zeta_{ph} = 0.036$ $\omega_{ph} = 0.175$ rad/s
$1/T_{\theta_2} = 0.56$ $l_p = 43.41$ ft CG = 38.7 % $\bar{c}$

Denominator: [0.65, 0.978] [0.036, 0.175]

N_α: -0.049 (22.3) [0.078, 0.211]
N_θ: -1.08 (0.081) (0.56)
N_q: -1.08 (0) (0.081) (0.56)
$N_{\gamma_{cg}}$: 0.049 (3.90) (-0.0005) (-3.40)
N_{γ_p}: -0.171 (-0.0005) [0.17, 1.97]

The time history responses, for a step input to the stick, for the unaugmented case 9 model are given in appendix A.

2.3.4 Comparison of Unaugmented Aircraft to MIL-F-8785C

The various specification parameters of the unaugmented aircraft, for the loading cases 7 to 9, are given below in table 1. These may then be compared with the requirements of MIL-F-8785C, reference 4.

Case	ζ_{sp}	ω_{sp}	T_{θ_2}	n/α	CAP	ζ_{ph}
7	0.51	1.18	1.89	3.49	0.40	0.038
8	0.54	1.28	1.85	3.57	0.46	0.047
9	0.65	0.978	1.78	3.71	0.26	0.036

Table 1 Unaugmented Aircraft Parameters

The level 1 short period damping requirements of reference 4 for the category C flight phase are $0.35 \le \zeta_{sp} \le 1.30$. Therefore all loading cases meet this requirement, however the damping ratio is nearer to the lower, under damped, limit.

The level 1 phugoid damping requirements of reference 4 are that ζ_{ph} must be at least 0.04. Therefore although case 8 meets this requirement, cases 7 and 9 do not, although they only just lie outside the boundary. This may not be a major problem for the control laws designed since the longer term, phugoid period, responses are all modified by the control laws. However, the MIL-F-8785C requirements are based upon the angle of attack response of the aircraft, regardless of the actual command variable, therefore although the phugoid response of the commanded variable may be well damped, the angle of attack damping may be less than 0.04 leading to the aircraft failing to comply to the MIL-F-8785C requirement.

Because of the closeness of the phugoid damping to the level 1 boundary it is unlikely that this will have a dramatic effect upon the ratings given. Additionally the dominance of the command response is likely to outweigh any slight non-compliance of the angle of attack phugoid damping.

Figure 7 shows the MIL-F-8785C short period frequency requirements for the category C flight phase. All three loading cases meet this requirement, however all three are near the lower level 1 boundary, demonstrating a rather slow short period for the given n/α. Recent work by Rossitto et al., reference 13, suggests that the lower level 1 CAP boundary of 0.16 may be too low, a figure of 0.5 may be more appropriate. If the boundary were raised to 0.5 all the loading cases considered would no longer meet the level 1 requirement, and would instead fall into level 2.

Either way the short period frequency is tending to the lower limit of the level 1 requirements. Coupled with the damping also tending to the lower limits for level 1, the unaugmented aircraft has a tendency for a slow, slightly under damped response.

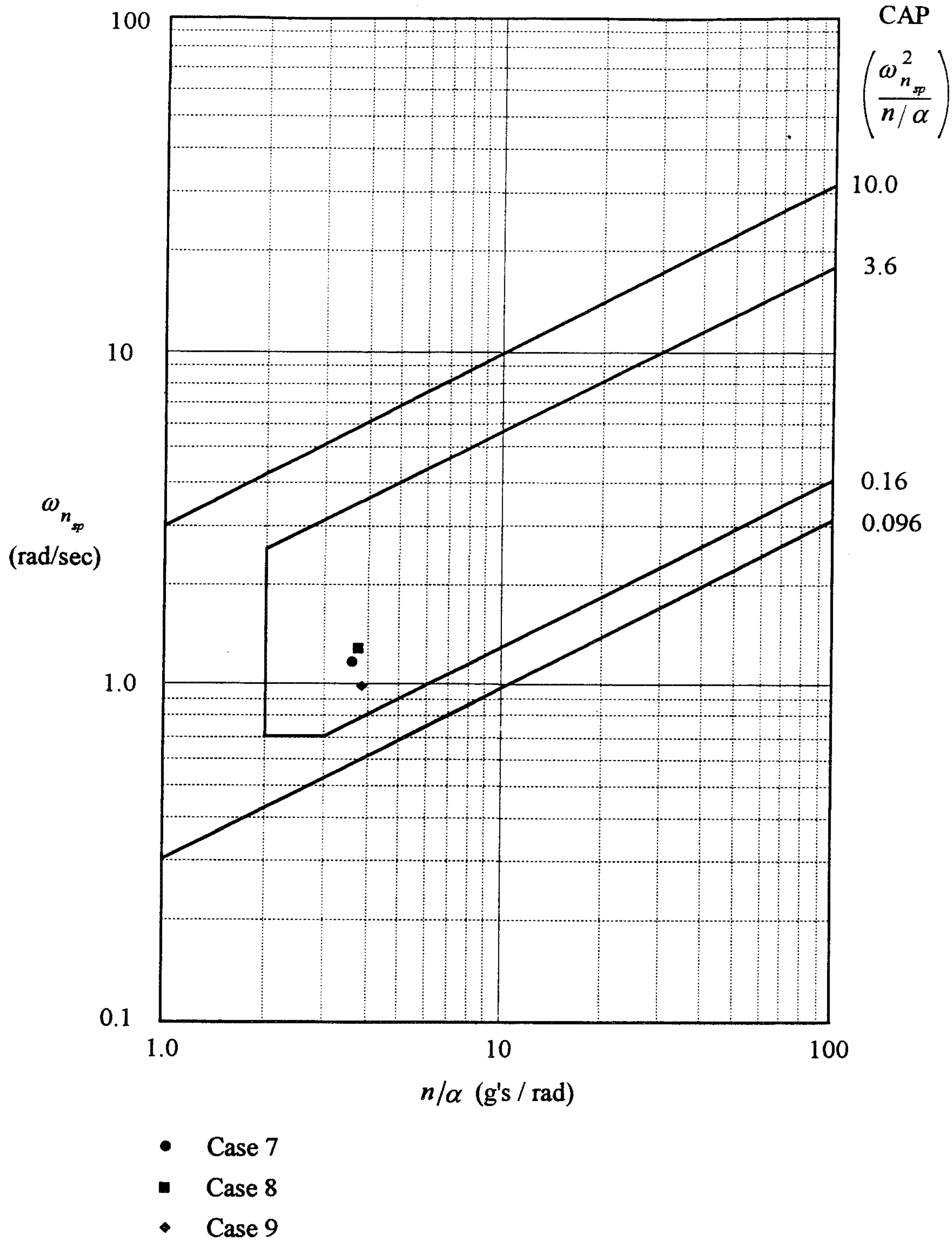


Figure 7 MIL-F-8785C Short Period Frequency Requirements

Although it would be possible to augment the basic short period mode of the designs to give a better damped and faster response, nearer the middle of the short period frequency and damping requirements, it was decided to leave these values at those of the unaugmented aircraft. In part this was done with the failure case in mind where upon suffering a flight control system failure the aircraft would revert to its basic dynamics. Thus it was felt that any augmentation should not dramatically alter the modal response of the aircraft. It was also anticipated that by maintaining these modal properties the required augmentation would be reduced and so the feedback gains would be smaller, thus reducing possible problems associated with large feedback gains. This philosophy holds for the angle of attack and pitch rate command systems, however larger gains are required for the flight path command systems since for these configurations the augmented response is less similar to the unaugmented response.

2.4 Detailed Design Definitions

Each control law configuration is assigned a unique configuration number, defined as follows:

Configuration X-Y-Z

where: X is the control law configuration set (P or I);
Y defines the CG location (7 to 9) and
Z is the control law design.

The control law design, Z, is defined as:

1 Angle of attack command (α)
2 Angle of attack rate command ($\dot{\alpha}$)
3 Pitch attitude command (θ)
4 Pitch rate command (q)
5 Flight path (at CG) command (γ_{cg})
6 Flight path (at CG) rate command ($\dot{\gamma}_{cg}$)
7 Flight path (at pilot station) command (γ_p)
8 Flight path (at pilot station) rate command ($\dot{\gamma}_p$)

Configurations with two digits define a mixed command system of short and long term response. For example control law 14 defines angle of attack command (1) short term and pitch rate command (4) long term.

2.4.1 Set P Configurations

Figure 8 gives the block diagram for all the set P configurations. The feedback gains were determined using the pole placement facility of MATLAB, reference 16. The command gain, K_c was defined so that a 10 lb step input to the control column produces an initial pitch acceleration of 0.1 rads/sec^2, as used in previous Calspan investigations, reference 3.

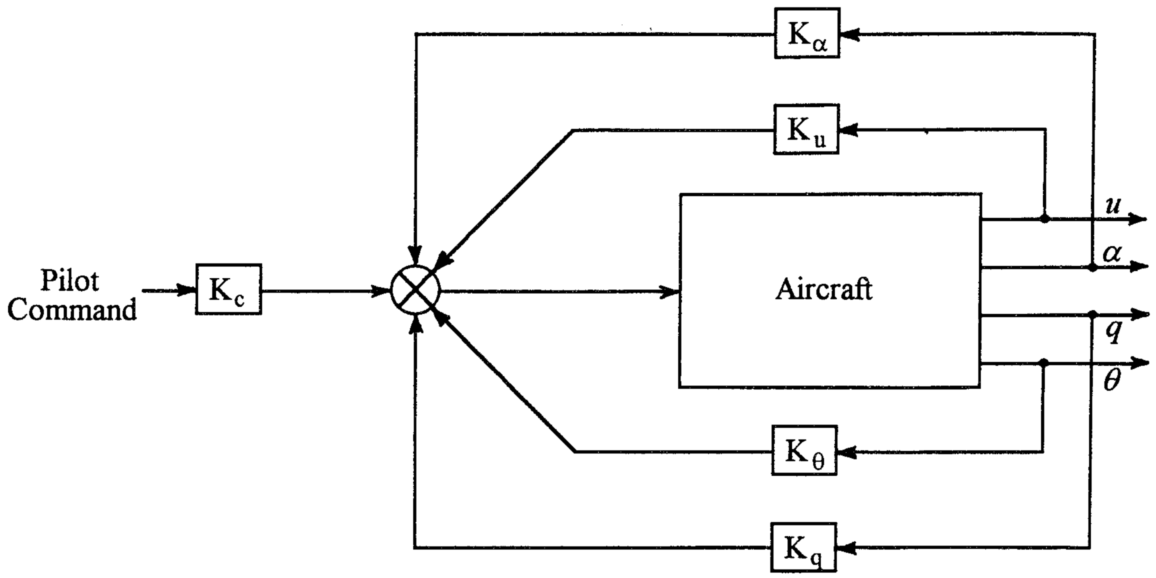


Figure 8 Set P Configurations Block Diagram

The following sections concern the design of the case 8 configurations, whose unaugmented denominator is given by:

Denominator: [0.54, 1.28] [0.047, 0.188]

Angle of Attack Command - Control Law 1

Section 2.3.2 defined the angle of attack numerator as:

N_α: -0.049 (25.3) [0.079, 0.211]

The additional zero at (s+25.3) is due to the pilot being ahead of the instantaneous centre of rotation. In order to produce a long term angle of attack command system the phugoid poles must cancel the complex angle of attack zeros. Thus neglecting centre of rotation effects the response is dominated by the short period poles which remain those of the unaugmented aircraft. Therefore the desired denominator to produce an angle of attack command system is:

D_α: [0.54, 1.28] [0.079, 0.211]

Angle of Attack Rate Command - Control Law 2

The angle of attack rate numerator is given by:

$N_{\dot{\alpha}}$: -0.049 (0) (25.3) [0.079, 0.211]

For an angle of attack rate command system the poles of the denominator must cancel the complex angle of attack zeros, as well as the zero at the origin, thus giving the rate command response. Additionally a pole must be added to give the short term response. This pole is added at (s+1.3) such that the speed of the pole is equivalent to the short period frequency of the unaugmented aircraft, and so maintains the basic speed of the aircraft's response across the range of both the angle and rate command controllers. The response of this system will therefore be dominated by the pole at (s+1.3). The required denominator to produce the angle of attack rate command system is therefore:

$D_{\dot{\alpha}}$: (0) (1.3) [0.079, 0.211]

Pitch Attitude Command - Control Law 3

The pitch attitude numerator is given by:

N_θ: -1.22 (0.083) (0.54)

To produce a pitch attitude command system the two zeros at (s+0.083) and (s+0.54), ($s+1/T_{\theta_1}$) and ($s+1/T_{\theta_2}$) respectively, must be cancelled by the long term poles of the denominator. The short period poles of the unaugmented aircraft are retained and therefore dominate the pitch attitude response. The required denominator to produce the pitch attitude command system is given by:

D_θ: (0.083) (0.54) [0.54, 1.28]

Pitch Rate Command - Control Law 4

The pitch rate numerator is given by:

N_q: -1.22 (0) (0.083) (0.54)

A pitch rate command system is produced by placing the poles of the denominator to cancel all the pitch rate zeros and introduce a pole at (s+1.3), as for the angle of attack command system. Thus the desired pitch rate denominator is:

D_q: (0) (0.083) (0.54) (1.3)

Flight Path at CG Command - Control Law 5

The flight path at CG numerator is given by:

$N_{\gamma_{cg}}$: 0.049 (4.11) (-0.0019) (-3.52)

In order to produce a flight path at CG command system the long term zeros of the numerator must be cancelled by poles of the denominator. In this case the relevant zeros are those at (s+4.11) and (s-0.0019). The zero at (s-3.52) is responsible for the non-minimum phase rate response observed in the flight path response, however this effect was not great and so no attempt was made to cancel this zero. The short period poles of the unaugmented aircraft were retained, which dominated the flight path response. This gives a required denominator of:

$D_{\gamma_{cg}}$: (4.11) (-0.0019) [0.54, 1.28]

Flight Path at CG Rate Command - Control Law 6

The flight path at CG rate numerator is given by:

$N_{\dot{\gamma}_{cg}}$: 0.049 (0) (4.11) (-0.0019) (-3.52)

To produce a flight path at CG rate command system the zeros at (s+4.11) and (s-0.0019) must be cancelled along with that at the origin. As for the previous rate command systems an additional pole is introduced at (s+1.3). The required denominator is given by:

$D_{\dot{\gamma}_{cg}}$: (0) (4.11) (-0.0019) (1.3)

Flight Path at Pilot Station Command - Control Law 7

The flight path at pilot station numerator is given by:

N_{γ_p}: -0.188 (-0.0019) [0.16, 1.96]

In order to produce a flight path at pilot station command system the denominator must cancel the long term zero at (s-0.0019). As with the previous angle command systems the unaugmented aircraft's short period is retained. Since this is almost cancelled by the complex zeros of the flight path numerator a further pole is introduced at (s+1.3) to assure similar short term response to the previous control laws. Thus the required denominator is:

D_{γ_p}: (-0.0019) (1.3) [0.54, 1.28]

Flight Path at Pilot Station Rate Command - Control Law 8

The flight path at pilot station rate command numerator is given by:

$N_{\dot{\gamma}_p}$: -0.188 (0) (-0.0019) [0.16, 1.96]

In order to produce a flight path at pilot station rate command system all the numerator zeros must be cancelled by the denominator poles. There is no requirement for additional poles. The required denominator is:

$D_{\dot{\gamma}_p}$: (0) (-0.0019) [0.16, 1.96]

Short Term Angle of Attack, Long Term Pitch Rate - Control Law 14

For the short term angle of attack response the conventional unaugmented short period is retained, however for the longer term pitch rate command the long term pitch rate numerator zeros at (s+0.083) and the origin must be cancelled by the poles of the denominator. Therefore the required denominator is:

$D_{\alpha q}$: (0) (0.083) [0.54, 1.28]

Short Term Angle of Attack, Long Term Flight Path CG Rate - Control Law 16

Here the short term response is the same as for the previous control law, however to produce the long term flight path at CG rate command the long term flight path at CG rate numerator zeros must be cancelled by the denominator poles at (s-0.0019) and the origin. The required denominator is given by:

$D_{\alpha\dot{\gamma}_{cg}}$: (0) (-0.0019) [0.54, 1.28]

Short Term Pitch Rate, Long Term Angle of Attack - Control Law 41

To produce a short term pitch rate and long term angle of attack command system the poles of the denominator must cancel the short term pitch rate numerator zero at (s+0.54), add a pole at (s+1.3) to give the short term response and cancel the long term complex angle of attack numerator zeros. Therefore the required denominator is:

$D_{q\alpha}$: (0.54) (1.3) [0.079, 0.211]

Short Term Flight Path CG Rate, Long Term Angle of Attack - Control Law 61

For the short term flight path at CG rate and long term angle of attack command system the denominator poles must cancel the short term flight path at CG denominator zero at (s+4.1), add a pole at (s+1.3) to give the short term response and cancel the long term oscillatory angle of attack numerator zeros. The required denominator is therefore:

$D_{\dot{\gamma}_{cg}\alpha}$: (4.1) (1.3) [0.079, 0.211]

Other Short Term, Long Term Combinations

Other combinations of short and long term dynamics are already described by the original eight control laws. For completeness these are listed below.

Control Law	Short Term	Long Term	Same As
13	α	θ	θ command
15	α	γ_{cg}	γ_{cg} command
17	α	γ_p	γ_p command
18	α	$\dot{\gamma}_P$	$\dot{\gamma}_P$ command
21	$\dot{\alpha}$	α	α command
31	θ	α	α command
51	γ_{cg}	α	α command
71	γ_p	α	α command
81	$\dot{\gamma}_P$	α	α command

Case 7 and 9 Control Laws

The identical design technique was used for the design of the loading cases 7 and 9 configurations. However only the following configurations were considered for these cases:

1 Angle of attack command;
3 Pitch attitude command;
4 Pitch rate command.

Set P Configuration Gains

Using the pole placement technique, for the appropriate aircraft models, the control law gains were derived for implementation in the system given in figure 8, and are given in table 2. Time history responses for the set P configurations are given in appendix B.

Additionally one other configuration was evaluated. This was the unaugmented aircraft for the mid CG case and was designated configuration B-8. The feedback gains for this configuration were set to zero, while the command gain was -0.009, determined as for the other configurations.

Configuration	K_u	K_α	K_q	K_θ	K_c
P-7-1	0.0004	-0.4367	0.0723	-0.0393	-0.010
P-7-3	-0.0002	0.4576	-0.5052	-1.2241	-0.010
P-7-4	-0.0001	0.5294	-0.6034	0.0003	-0.010
P-8-1	0.0006	0.0180	-0.0134	-0.0355	-0.009
P-8-2	0.0006	1.3222	0.0008	-0.0355	-0.009
P-8-3	-0.0002	0.9597	-0.5330	-1.3413	-0.009
P-8-4	-0.0002	0.9597	-0.4660	0.0	-0.009
P-8-5	-0.0086	6.5827	-3.6157	-9.0793	-0.011
P-8-6	-0.0048	-1.2416	-3.2326	0.3041	-0.011
P-8-7	-0.0044	2.0805	-1.1335	-2.8415	-0.010
P-8-8	-0.0024	-0.0051	0.0164	0.0482	-0.009
P-8-14	-0.0025	0.1302	-0.0583	-0.1395	-0.009
P-8-16	-0.0024	-0.0051	0.0164	0.0482	-0.009
P-8-41	0.0012	1.0062	-0.4276	-0.0348	-0.009
P-8-61	0.0051	-1.0890	-3.2677	-0.0297	-0.011
P-9-1	0.0006	0.0148	-0.0198	-0.0404	-0.010
P-9-3	-0.0002	0.5081	-0.6094	-0.8880	-0.010
P-9-4	-0.0002	0.5081	-0.6334	0.0	-0.010

Table 2 Set P Configuration Gains

2.4.2 Set I Configurations

The set I control laws incorporate proportional plus integral controllers acting upon pitch rate, flight path at CG rate and flight path at the pilot station rate. The control laws were designed using the reduced order model to determine the angle of attack, pitch rate and command parameter error feedback gains. The forward speed feedback gain was then adjusted so that the long term response of the full order model gave the required steady state step response.

The following sections describe the design of the set I control laws for loading case 8.

Proportional Plus Integral Pitch Rate Command

The reduced order control law structure used for the design of this configuration is given in figure 9.

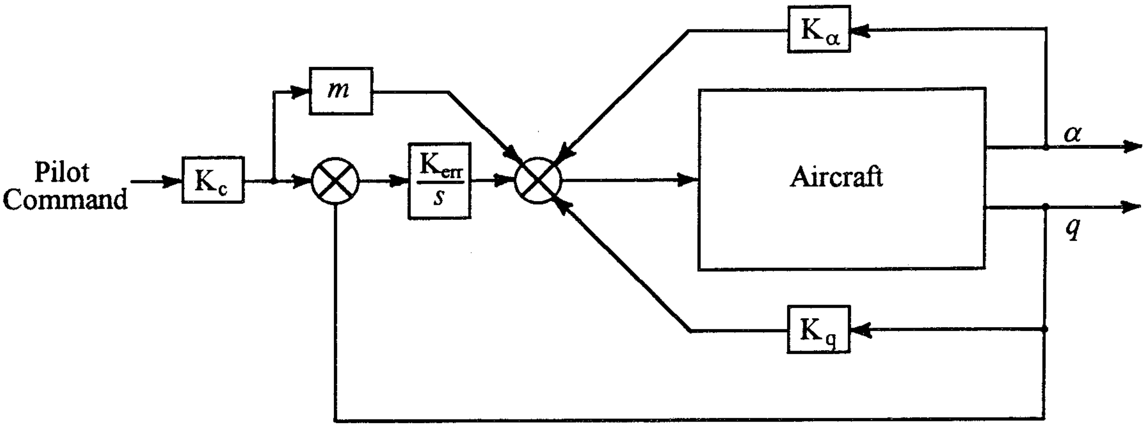


Figure 9 Reduced Order PPI Pitch Rate Command Control Law Structure

As well as the two "natural" states of constant speed aerodynamic flight, angle of attack and pitch rate, a third state is introduced, the integral of the pitch rate error $(q\text{-}q_d)$, which is defined as:

$$\varepsilon_q = \int (q - q_d) \tag{11}$$

Therefore $$\dot{\varepsilon}_q = (q - q_d) \tag{12}$$

The state space equation for this system is therefore modified to:

$$M\underline{\dot{x}} = A\underline{x} + B\eta + Nq_d \tag{13}$$

or in full:

$$\begin{bmatrix} (\mathrm{m} - Z_{\dot{\alpha}}) & 0 & 0 \\ -M_{\dot{\alpha}} & I_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{q} \\ \dot{\varepsilon}_q \end{bmatrix} = \begin{bmatrix} Z_\alpha & (\mathrm{m}U_e + Z_q) & 0 \\ M_\alpha & M_q & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ q \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} Z_\eta \\ M_\eta \\ 0 \end{bmatrix} \eta + \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} q_d \tag{14}$$

With elevator control law:

$$\eta = mq_d - K\underline{x} \tag{15}$$

pre-multiplying equation 13 by the inverted mass matrix M^{-1} gives:

$$\underline{\dot{x}} = (A' - B'K)\underline{x} + (B'm + N)q_d \tag{16}$$

where $A' = M^{-1}A$ and $B' = M^{-1}B$.

Therefore the poles of the matrix $(A' - B'K)$ will give the desired modal performance. As with the set P configurations two of these poles were specified so that the unaugmented aircraft's short period dynamics were retained. Two choices were made for the third pole, introduced by the integral loop. Firstly the pole was placed at $(s+1.3)$ as for the set P configurations, and secondly at $(s+6)$. The second choice was made to speed up the response due to this pole, especially important if inexact pole/zero cancellation occurs with the zero introduced by the feedforward path, especially likely if the evaluation speed is allowed to drift off the design speed. However the faster pole requires larger values of feedback gain, with their associated drawbacks.

In order to cancel the integrator pole the feedforward gain is defined as:

$$m = \frac{k_{\dot{\varepsilon}_q}}{z_i} \tag{17}$$

where z_i is the zero introduced by the feedforward path and is defined to cancel the integral pole.

These gains are then implemented in the full order model of figure 10 where the forward speed gain is iteratively adjusted to give the desired steady state pitch rate response.

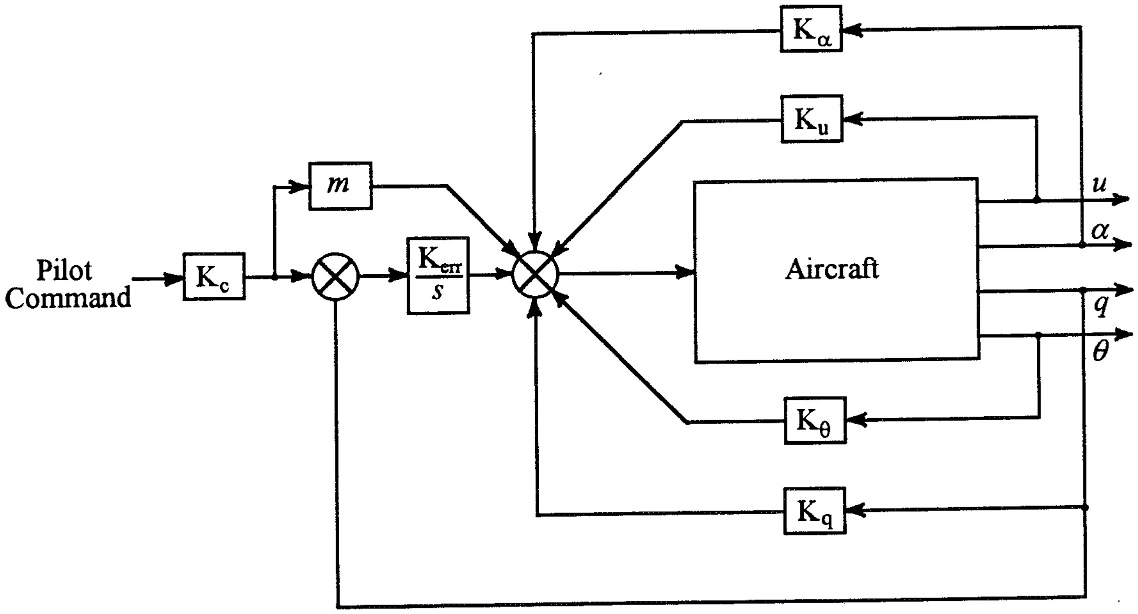


Figure 10 Full Order PPI Pitch Rate Command Control Law Structure

Proportional Plus Integral Flight Path at CG Rate Command

The same design process was used for the flight path at CG rate command system as was used for the pitch rate command system. The system block diagrams are similar to those for pitch rate, figures 9 and 10, however with flight path error rate fed back through the proportional plus integral controller. However the error signal is defined as follows:

$$\varepsilon_{\dot{\gamma}_{cg}} = \int\left(\dot{\gamma}_{cg} - \dot{\gamma}_{cg_d}\right) \tag{18}$$

Therefore $$\dot{\varepsilon}_{\dot{\gamma}_{cg}} = \left(\dot{\gamma}_{cg} - \dot{\gamma}_{cg_d}\right) \tag{19}$$

or from equation 3

$$\dot{\varepsilon}_{\dot{\gamma}_{cg}} = \left(q - \dot{\alpha} - \dot{\gamma}_{cg_d}\right) \tag{20}$$

The state space equation for this system becomes:

$$M\underline{\dot{x}} = A\underline{x} + B\eta + N\dot{\gamma}_{cg_d} \tag{21}$$

In full:

$$\begin{bmatrix} (\mathrm{m} - Z_{\dot{\alpha}}) & 0 & 0 \\ -M_{\dot{\alpha}} & I_y & 0 \\ 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{q} \\ \dot{\varepsilon}_{\dot{\gamma}_{cg}} \end{bmatrix} = \begin{bmatrix} Z_\alpha & (\mathrm{m}U_e + Z_q) & 0 \\ M_\alpha & M_q & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ q \\ \varepsilon_{\dot{\gamma}_{cg}} \end{bmatrix} + \begin{bmatrix} Z_\eta \\ M_\eta \\ 0 \end{bmatrix} \eta + \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \dot{\gamma}_{cg_d} \tag{22}$$

With elevator control law:

$$\eta = m\dot{\gamma}_{cg_d} - K\underline{x} \tag{23}$$

pre-multiplying equation 21 by the inverted mass matrix M^{-1} gives:

$$\underline{\dot{x}} = (A' - B'K)\underline{x} + (B'm + N)\dot{\gamma}_{cg_d} \tag{24}$$

Again the performance of the system is defined by the poles of the $(A' - B'K)$ matrix. The rest of the analysis is the same as that for the pitch rate command system.

Proportional Plus Integral Flight Path at Pilot Station Rate Command

The same design process was used for the flight path at pilot station rate command system as was used for the flight path at CG rate command system, with the following differences:

$$\varepsilon_{\dot{\gamma}_p} = \int\left(\dot{\gamma}_p - \dot{\gamma}_{p_d}\right) \tag{25}$$

Therefore $$\dot{\varepsilon}_{\dot{\gamma}_p} = \left(\dot{\gamma}_p - \dot{\gamma}_{p_d}\right) \tag{26}$$

and from equation 9

$$\dot{\varepsilon}_{\dot{\gamma}_p} = \left(q - \dot{\alpha} + \frac{l_p}{V}\dot{q} - \dot{\gamma}_{p_d}\right) \tag{27}$$

The state space equation of this system in given by:

$$M\underline{\dot{x}} = A\underline{x} + B\eta + N\dot{\gamma}_{p_d} \tag{28}$$

In full:

$$\begin{bmatrix} (\mathrm{m} - Z_{\dot{\alpha}}) & 0 & 0 \\ -M_{\dot{\alpha}} & I_y & 0 \\ 1 & l_p/U_e & 1 \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{q} \\ \dot{\varepsilon}_{\dot{\gamma}_p} \end{bmatrix} = \begin{bmatrix} Z_\alpha & (\mathrm{m}U_e + Z_q) & 0 \\ M_\alpha & M_q & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ q \\ \varepsilon_{\dot{\gamma}_p} \end{bmatrix} + \begin{bmatrix} Z_\eta \\ M_\eta \\ 0 \end{bmatrix} \eta + \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \dot{\gamma}_{p_d} \tag{29}$$

where l_p is the pilot moment arm.

With elevator control law:

$$\eta = m\dot{\gamma}_{p_d} - K\underline{x} \tag{30}$$

pre-multiplying equation 28 by the inverted mass matrix M^{-1} gives:

$$\underline{\dot{x}} = (A' - B'K)\underline{x} + (B'm + N)\dot{\gamma}_{p_d} \tag{31}$$

Again the performance of the system is defined by the poles of the $(A' - B'K)$ matrix. The rest of the analysis is the same as that for the pitch rate and flight path at CG rate command systems.

Set I Configuration Gains

For the datum loading case 8 each of the above control laws were designed with integrator poles at (s+1.3) and (s+6), giving a total of six configurations. Pitch rate command systems for both integrator poles were also designed for loading cases 7 and 9. The same numbering system was used for the set I configurations as for set P, an A was added to the configuration number to identify those with the integrator pole at (s+6). Table 3 gives the gains for the set I configurations. Time history responses for the set I configurations are given in appendix C.

Configuration	K_u	K_α	K_q	K_θ	K_c	K_{err}	m
I-7-4	-0.0010	0.0125	-1.6080	0.0	0.0035	-3.5072	-2.70
I-7-4A	-0.0010	0.0576	-7.4218	0.0	0.004	-16.1871	-2.70
I-8-4	0.0035	2.1303	-1.1517	0.0	0.004	-2.9566	-2.27
I-8-4A	0.0200	9.8319	-5.3154	0.0	0.004	-13.6456	-2.27
I-8-6	-0.0045	-0.8263	-1.1517	0.0	0.004	-2.9566	-2.27
I-8-6A	-0.0110	-3.8137	-5.3154	0.0	0.004	-13.6456	-2.27
I-8-8	-0.0045	-0.8263	-0.6343	0.0	0.004	-2.9566	-2.27
I-8-8A	-0.0110	-3.8137	-2.9274	0.0	0.004	-13.6456	-2.27
I-9-4	0.0035	1.6086	-1.2127	0.0	0.005	-2.7416	-2.11
I-9-4A	0.020	9.0850	-5.9226	0.0	0.005	-12.6534	-2.11

Table 3 Set I Configuration Gains

3. EXPERIMENT IMPLEMENTATION

3.1 Description of Simulator

The engineering simulator used in this investigation was designed, built and operated by British Aerospace Regional Aircraft, Hatfield. It is a fixed base device with a single window dusk/night visual display and hydraulic control loading. The cockpit was representative of a Avro International Aerospace RJ series aircraft with a Phase II avionics fit, however for the purpose of these evaluations was only flown from the left hand seat.

Representative of the RJ series there were four throttle levers, however the outer two were closed to leave the two inner levers operable to control the two engines of the modelled aircraft. Full flap and undercarriage deployment were selected throughout the evaluations and were not variables in the investigation.

The instrumentation was that of the RJ Phase II avionics fit and comprised EFIS Primary Flight Displays, Navigation Displays and servo altimeters on both sides and a Distance Bearing Indicator on the left hand side. The only other display relevant to the evaluations was the LED primary engine display of N1. Height callouts based on the Sundstrand Mk5 GPWS were enunciated at 500, 100, 50, 40, 30, 20 and 10 feet as well as a "minimums" callout at the decision height.

The simulations were run on a dedicated DEC VAX4000 computer, using an iteration rate of 50 Hz. Interaction with an operator was possible via menu selections on a terminal mounted in the cockpit.

Several modifications to the simulation were made for the purpose of this investigation. Firstly pitch trim via the electric thumb control on the column was implemented to relieve the pilot held load on the column. Secondly the ILS glideslope/runway intercept point was moved 1000 feet into the runway, beyond its normal position. This was for the pitch offset task as described in section 4.1. Lastly several modifications were made to the outside world visual display, again for task definition and described in section 4.1.

3.2 Pitch Control Law Implementation

The pitch control laws were implemented in the simulator as given in figures 8 and 10 with the control law gains of tables 2 and 3. The simulator utilised the full six degree of freedom aircraft model and so there were some differences between the actual responses of the simulator and those of the small perturbation model used in the design process.

The main difference concerned the command gain K_c where it was necessary to increase the command gain of the full model in order to obtain the required initial pitch acceleration of 0.1 rad/sec^2. This required multiplication by a factor of between 17 and 23. Had time allowed further verification of the configurations as implemented in the simulator would have been performed, and this would likely have corrected any other appreciable differences between the responses of the small perturbation and full models.

3.3 Feel System and Actuator Dynamics

The feel system was hydraulically operated, controlled by a dedicated computer running at 500 iterations per second. Nominally frictionless jacks were used. The system is capable of simulating spring forces, friction, damping, end stops and constant loads.

For the investigation the control loadings comprised a spring force of 12 lb/inch with 0.5 lb/inch/sec damping. These values should have been reliably set by the hardware. The dynamic characteristics of the feel system itself are not known.

The simulated control system incorporated perfect actuators (the actuators were not actually modelled, so that the actual elevator would always be equal to demanded elevator). The maximum delay between pilot input and demand output was 20 milliseconds.

The lateral feel system was fixed at that of the basic simulator characteristics.

3.4 Lateral Model

The lateral model used in this investigation was that of the baseline generic aircraft model. The spiral mode was neutrally stable, Dutch Roll and Roll Subsidence characteristics are given below.

Case 7	$\omega_{dr} = 1.189$	$\zeta_{dr} = 0.4737$	$\tau_{dr} = 0.641$
Case 8	$\omega_{dr} = 1.296$	$\zeta_{dr} = 0.5640$	$\tau_{dr} = 0.869$
Case 9	$\omega_{dr} = 1.154$	$\zeta_{dr} = 0.5467$	$\tau_{dr} = 0.692$

3.5 Ground Effect Model

The ground effect model used in this investigation was that of the baseline generic aircraft model. It consists of increments on lift, pitching moment, downwash and local tailplane dynamic pressure that are dependent on height above the ground and angle of attack. The ground effect terms are zero for all heights above 104.34 feet above ground level and are increased to a given value when the aircraft is on the ground. The scheduling of the increments is commercially sensitive.

3.6 Thrust Model

The thrust model used was again that of the baseline generic aircraft and is company confidential. The model used represents an engine that does not yet exist and so is based on manufacturer's predictions.

The engine is modelled as an N1 demand system, the dynamics being represented as a rate limited lag response to a throttle movement. The rate limits for acceleration and deceleration are different, and are functions of the core speed N2. Thrust is modelled using gross thrust and airflow in order to calculate momentum drag effects correctly. Values for the N1/thrust relationship are taken from manufacturer's estimates and vary with altitude, Mach number and temperature.

3.7 Calibration

Ideally, detailed calibration would have been performed before any evaluations. Unfortunately due to time tabling constraints it was not possible to perform detailed pilot in the loop calibration of the control laws prior to the first evaluation session. This session could have been changed to calibration rather than evaluation, however the availability of the simulator, prior to its decommissioning for moving to another site, and of the evaluation pilots was limited and it was not desired to lose any evaluation sessions.

As a result the main pre-evaluation calibration was performed off-line, although the P-8 configurations were also tested on-line to verify general response.

Due to problems with some of the configurations that were exposed during the evaluations it was decided to perform a "calibration" session when the simulator was available. This was performed on the 10 November 1993 after pilots A, B and C had completed their evaluations, but before pilot D's evaluation session. The scope of these "calibrations" was to determine any features of the configurations which may have effected the ratings awarded, and was performed by the author. Ideally pre-evaluation calibration would have corrected these problems, however this was not possible within the constraints of the investigation.

Features of the configurations which were identified in this session and that are believed to have affected the evaluations are presented below.

P-8-1	The baseline angle of attack command system felt conventional, no problems were identified.

P-8-2	This configuration gave a very twitchy response requiring considerable compensation not to set off an oscillatory response. PIO prone, could lose control if pilot gain gets too high.
P-8-3	Requirement to hold forces to maintain a new attitude, but these could be easily trimmed out. Attitude stable, it would hold an attitude hands off. With no trimming it required a force of about 4 lbs to hold the glideslope from level flight. Otherwise it felt fairly conventional.
P-8-4	In the longer term response there was a definite tendency for the nose to drop. This could be counteracted by a quick nose up burst of trim, after which attitude was held well. It is likely that this was due to inexact pole/zero cancellation. As a result the evaluation pilots will almost certainly have felt the need to use a small amount of trim with this configuration.
P-8-5	This required excessive forces to pitch the nose of the aircraft down, with insufficient trim authority to hold this force, although only just. The force required to hold the glideslope was in excess of 20 lbs. However this configuration was definitely flight path stable.
P-8-6	This configuration was not perfectly implemented, in that when power was reduced the nose dropped causing an uncommanded change in flight path. There was again a need to hold a little back force throughout the descent. A burst of trim of about 1 second was sufficient to counteract this force. Generally this configuration was flight path stable.
P-8-7	Lower stick forces required than for P-8-5. As for P-8-5 when the power was reduced the nose rose to maintain the flight path (lower speed required higher angle of attack, and therefore attitude, to maintain lift and so flight path). Otherwise this was far more pleasant than P-8-5, with adequate trim authority. If untrimmed a constant force of approximately 10 lbs was required to maintain the glideslope. Again this configuration was flight path stable.
P-8-8	As for the previous rate command configurations a definite tendency for the nose to drop if left unattended. Again a quick burst of trim, nose up, relieved the residual force.
P-8-14	This configuration felt nice, with the nose going down with power reduction. There were slight residual forces, however these alternated between pull and push and were comfortable to hold. There was a very slight tendency for the nose to drop in the level section of the evaluation if left alone, leading to a possible requirement for a very slight burst of trim to counteract this, but not as great as for most configurations. There was no real need to trim with this configuration.
P-8-16	The nose dropped with reduction in power, and again there was a slight need for nose up trim.

P-8-41	No trim requirement at all. The nose dropped when the power was reduced and there was a requirement to pull back to acquire the glideslope and stop the pitching. However there was no need to trim when the glideslope was acquired.
P-8-61	The stick forces for this configuration were excessive. It required considerable force to initiate a manoeuvre which gave a very sluggish response, requiring compensation in the prediction of the response. However once a new flight path was acquired it was held fairly well with no need to trim at all. The high stick forces were only transitional. The flare, however was almost impossible, unless started very early. Non-real-time checks performed after the evaluations showed that the command gain K_c was incorrectly specified as 1/10 of the required value. The pilots therefore had to use forces 10 times higher than for the other configurations.
I-8-4	When the power was reduced the nose dropped, but only slightly, settling to a slightly lower attitude. Some oscillation was noted in the attitude response, the response was not dead band. There was no trimming requirement and control was fairly crisp, except for the oscillatory response.
I-8-4A	Much like I-8-4 but crisper. It gave better attitude control, holding the attitude better when the stick was released and giving a less oscillatory response. There was no pitching with power changes, no requirement to trim and it was better at holding attitude than I-8-4.
I-8-6	When power was reduced the nose rose to maintain the flight path. It didn't quite manage to hold $\dot{\gamma} = 0$ but tried pretty hard. There was no requirement to trim.
I-8-6A	There was less nose up with power reduction than with I-8-6. Generally a pitch down tendency if not checked by the stick, although there was no need to trim. This configuration did not feel as pleasant as I-8-6.
I-8-8	A definite nose down pitching with power reduction, although only a small attitude change and it did stabilise. In the longer term it did tend to drift nose down slightly although there was no need to trim.
I-8-8A	The nose pitched up with power reduction although it was unable to hold the flight path. Generally a slight nose down tendency throughout.
P-7-1	As for P-8-1, but slight trimming required when on glideslope.
P-7-3	As for P-8-3, additionally good at holding attitude and heavy in the flare.

P-7-4	Nose pitched with power changes. No real need to trim. Otherwise much as P-8-4, except not very good at holding attitude.
I-7-4	Held the attitude nicely with power changes. No need to trim, slightly oscillatory in response.
I-7-4A	This seemed crisper than I-7-4 with no oscillation in the attitude response. It held attitude very well, even with power changes.
P-9-1	As for P-7-1.
P-9-3	As for P-7-3.
P-9-4	As for P-7-4.
I-9-4	Slightly oscillatory response. Nose tended to drop, but only slightly, with reduction in power. No trimming required.
I-9-4A	This was oscillatory in the attitude response, or at least gave an observable attitude dropback. A very slight, approximately 1°, nose down attitude change.

For most of the configurations, especially the rate command systems, there was a tendency for the nose to drop giving a requirement to trim out this effect. This was found to be true regardless of whether the aircraft was fast, exactly on speed or slow. This is believed to be a problem with the implementation, probably due to the differences in the small perturbation model used for the design, and the full model used in the engineering simulator. These effects have been taken into account in the discussions of section 6 in this report.

Had pre-evaluation calibration been performed these configurations would have been corrected, however the effect was minimal and is unlikely to have affected the ratings given. More importantly two configurations, P-8-5 and P-8-61, both required excessive forces for control, as well as several other configurations requiring slightly higher forces than might have been ideal. These configurations would have been modified had earlier calibration been performed.

As discussed above the excessive forces of P-8-61 were due to incorrect setting of the command gain. The problems of P-8-5 are likely to be the same as for the other flight path and pitch attitude command systems. The sensitivity set by the initial pitch acceleration overshoot of 0.1 rad/sec^2 works well for the angle of attack and rate command systems but is not adequate for the pitch attitude and flight path command systems. An alternative mechanism is required for these systems, perhaps incorporating gain scheduling dependant upon the force applied by the pilot, so that as greater forces are applied by the pilot the command gain increases, therefore lower forces are required for large flight path changes, such as in the flare, than are required for a constant command gain system.

However in this investigation the command gain defined by the pitch acceleration overshoot of 0.1 rad/sec^2 worked pretty well for almost all configurations.

4. EVALUATION PROCEDURE

4.1 Evaluation Sequence

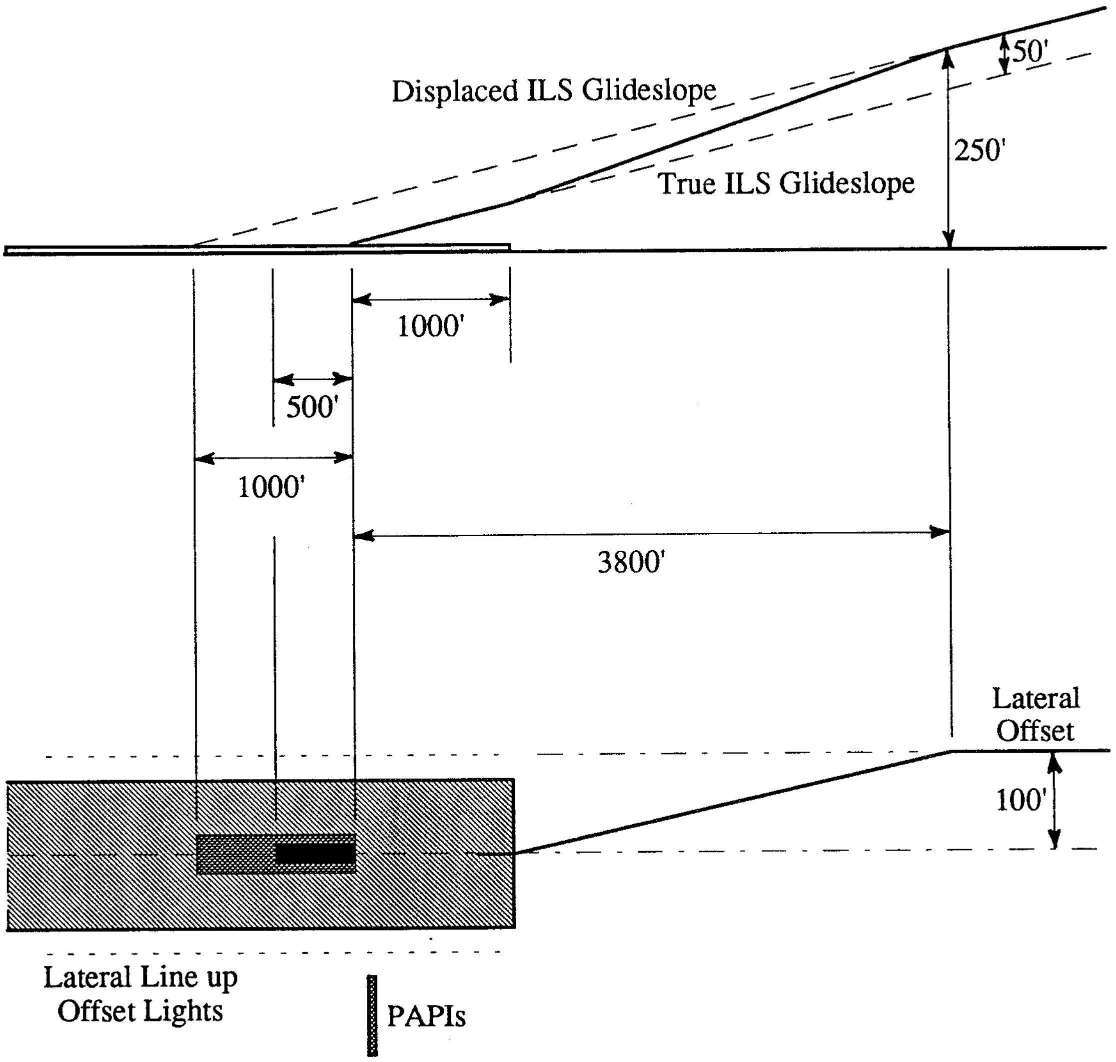
The evaluation sequence comprised two approaches for each configuration, one instrument the other visual. A third approach was available at the evaluation pilot's request. The aircraft was handed over to the evaluation pilot in trim and in level flight at 1500 feet QNH, approximately 1240 feet agl and 5 miles from the threshold. The aircraft was positioned approximately two dots below the true glideslope. The pilot was tasked to maintain level flight until acquiring the 3° glideslope, then descend on the glideslope, maintaining the speed throughout the approach at 126 kts IAS.

The evaluation sequence was derived from those used for previous handling quality investigations, and given in reference 3. In these investigations the pilots were tasked to visually fly a lateral offset of about 200 feet from the runway centreline, and correct onto the centreline at a height of 200 feet, in order to provide secondary tasking for the pilot, thus preventing pre-occupation with the pitch task. By taking the pilot's attention away from the primary pitch control task it is hoped that any deficiency in the pitch axis may become apparent. However this does not mean that a deficiency in this axis will necessarily be exposed. As a result it was decided to perform a pitch offset as well as a lateral offset, so that the pilot was forced to actively manoeuvre the aircraft in pitch close to the ground, at a height of approximately 200 feet. It was hoped that this would expose additional problems in the pitch axis that may be missed by the lateral offset, however it is acknowledged that this manoeuvre may cause concern to the crew of an in-flight simulator.

The first approach was an instrument ILS. The ILS glideslope was offset so that the glideslope/runway intercept was displaced 1000 feet along the runway, equating to a height error of approximately 50 feet throughout the approach. The pilot was tasked to fly accurately the flight directed ILS to a point 3800 feet short of the true glideslope/runway intercept. This point is at a height of 250 feet agl and is 50 feet above the true glideslope. The correction point at 3800 feet from glideslope/runway intercept was enunciated to the pilot by an aural tone. At this point the pilot went visual and attempted to land the aircraft in the desired box, as marked on the runway, figure 11.

The use of the flight director was to ensure repeatability of the task so that the pilot was always on the displaced glideslope at the correction point. The only other parameter that the pilot had to control was the speed, which had to be 126 kts at the correction point.

The second approach was a visual approach with the pilot flying the glideslope using the PAPIs and laterally lining up with a series of lights, either side of the runway, offset from the centreline by 100 feet. Ideally the offset would have been 200 feet either side of the runway centreline, however due to deficiencies in the simulated lateral flying qualities, most probably due to the lack of motion cues coupled with the oversensitivity of the direct roll control system implemented, this task became solely that of trying to control the aircraft laterally. In order that these deficiencies did not bury the longitudinal handling qualities the offset was reduced to 100 feet, which was found to be laterally controllable and permit attention to the pitch axis. Again at the correction point 3800 feet from the glideslope/runway intercept, this time on the true ILS glideslope and at a target height of 200 feet, the pilot went visual upon hearing the aural tone and corrected to land the aircraft in the desired box.



■ Desired Touchdown Box (500' long, ± 10' of centreline)

▨ Adequate Touchdown Box (1000' long, ± 20' of centreline)

Figure 11 Approach and Landing Evaluation Tasks

The evaluation was split into two sections, the approach and the flare and touchdown. The approach was taken to be that portion covering the correction, the flare and touchdown being self defined. The earlier portion of the approach was not directly rated, but was used to gain familiarity with the configuration and ensure adequate control to be at the correction point at the target speed, however deficiencies in the configuration were noted and their effect was allowed to colour the rating awarded by the pilot.

The definition of desired and adequate performance levels for the approach segment were somewhat subjective. The main metric being the airspeed of 126 kts, ± 3 kts for desired, and ± 6 kts adequate. However this only covers the start of the correction, and not the actual correction. Therefore more of a pilot opinion, attained-performance-enhanced, subjective rating was given for the approach portion.

Performance levels for the flare and touchdown were slightly easier to define. Values were taken from previous Calspan investigations and modified where relevant to meet the requirements of this particular investigation. The touchdown zones were marked on the runway as a dim box with green lights at the corners for desired, and a bright box with amber lights at the corners for adequate, figure 11. The desired touchdown box was 500 feet long and 20 feet wide (10 feet either side of centreline), with its leading edge aligned with the glideslope/runway intercept point, which was 75 feet beyond the PAPIs. The adequate touchdown box was 1000 feet long, 40 feet wide and started at the same point on the runway as the desired box.

Initially the boxes were placed so that they started 250 feet beyond the glideslope/runway intercept point as in reference 3, however it was found that this was an excessive flare for the aircraft model used in the investigation. In part this may have been due to the rather strong ground effect model which caused the aircraft to pitch nose down rather more than the pilots were expecting. As a result it was decided to bring the boxes back to align their edge with the glideslope/runway intercept point. For the visual approach this resulted in the boxes starting 75 feet beyond the PAPIs. This caused no problems and did after all assure that the pilot had to flare the aircraft to land in the desired or adequate boxes for the visual approach.

Desired touchdown sink rates from reference 3 were 0-3 fps for desired, and 3-6 fps for adequate. However being a fixed based ground simulator, limited to a night visual, the cues of sink rate to the pilot were poor and so these figures were not directly used to determine the performance. They were however noted and discussed when giving the pilot rating. A useful cue of sink rate that the pilots were able to use was the audio height call out below 500 feet, as described in section 3.1.

The lateral flying qualities of the aircraft did not aid in the evaluation of the configurations and so less attention is paid to the lateral touchdown location accordingly. Finally airspeed. The target touchdown speed was 121 kts, however this was not taken as a primary performance target, as it was basically a function of when the pilot closed the throttles. The suggested procedure was to close the throttles approximately half way between the threshold and the start of the touchdown box, and accept whatever touchdown speed resulted. A low speed generally flagged a floating configuration, in which case this should be apparent in the rating and pilot comments.

One of the main reasons for accurately maintaining speed was that the control laws were only accurate for one speed, and so if the speed was allowed to alter dramatically the response of the aircraft may no longer represent that which was designed.

4.2 Test Procedure

The evaluation pilots were informed that the primary purpose of the evaluations was to investigate the commanded aircraft response that pilots prefer. They were told that in total there were approximately thirty different flight control law configurations to be evaluated, all confined to the pitch axis, that covered two primary configuration sets and three different CG locations, forward, mid and aft. The mid CG location being the datum which would be used for most evaluations. They were also informed of the command parameters under investigation and of the control law structures of the two configuration sets.

They were told that all the control laws were designed using a small perturbations model of the host aircraft, however the evaluations would be performed on the full aircraft model. As a result the control laws were only accurate for the design speed, and so it was important that speed was maintained at the target approach speed throughout the evaluation. They were briefed that trim, via the thumb control on the yoke, was available if required, and that when used it was implemented to release the force being applied to the stick.

The pilots were briefed that the host aircraft for the configurations was a generic low wing twin turbofan powered regional passenger aircraft with a 90,000 lb evaluation weight. They were also given approximate power settings and attitudes to maintain level flight and the glideslope as:

Level flight:	68% N_1 and 4° attitude;
3° glideslope:	53% N_1 and 1° attitude.

All evaluations were performed "blind", that is the pilots were unaware of the configuration they were evaluating. This is a well established technique for this type of comparative investigation and did not produce any problems. The pilots were able to cope with the different demands of the different configurations, the main adaptation in their technique was whether trim was required or not. This never posed a problem and the pilots were able to give a clear impression of their opinions on what they observed, rather than give what they thought they saw or wanted to see given their pre-conceptions of different command systems.

The evaluation pilots were first given several practice approaches with a baseline configuration to gain experience with the basic response of the aircraft, the simulator and the runway markings. Additionally this allowed familiarity with the lateral characteristics which were constant throughout the evaluations. Initially it had been planned to use the baseline unaugmented aircraft for this purpose. However in the first evaluation session it was found that the unaugmented aircraft required higher stick forces than the augmented configurations. As a result pilot A down rated his initial evaluated configuration due to its lighter forces and perceived twitchier response than that to which he had become accustomed. Once re-calibrated to these lighter stick forces this was no longer a problem. Subsequently the generally well behaved configuration P-8-1, angle of attack command with mid CG, was used for familiarity, and no further problems were encountered.

After the two evaluation approaches, or three if requested, the pilot completed the comment card, figure 12, and assigned both Cooper-Harper and PIO ratings to the configuration, figures 13 and 14 respectively.

4.3 Evaluation Pilots

Four evaluation pilots took part in the investigation. All four are former RAF test pilots with previous handling qualities evaluation experience.

Pilot A - Roger Bailey

Acquired nearly 5000 hours flying C-130 Hercules with the RAF followed by 1000 hours as a flying instructor. After graduating from the USAF TPS he spent three years at RAE Bedford, half of which as squadron commander, primarily working on the Civil Avionics Programme as well as supporting systems and handling qualities trials on the Tornado and various engineering simulators. Since 1990 he has been the Chief Test Pilot at the College of Aeronautics.

Pilot B - Les Evans

A former Harrier and Hunter pilot with the RAF. After training at ETPS he spent three years as squadron commander at RAE Bedford supporting various trials on Tornado and Harrier fast jets. After leaving the RAF spent two years as fixed wing tutor at ITPS. Currently flies the Boeing 747 with British Airways.

Pilot C - Mervyn Evans

The majority of his career in the RAF was spent flying fast jets. Following training at the US Navy TPS spent three years at RAE Farnborough followed by three years as principle tutor, fixed wing, at ETPS. Has had considerable involvement in fly-by-wire research and training including the ETPS ASTRA Hawk and Calspan Learjet. He is currently Principle Test Pilot at ITPS, Cranfield.

Pilot D - D A Z James

The majority of his 27 years in the RAF was spent flying fast jets including the Jet Provost, Hunter and Harrier. After graduating from ETPS he spent four years at RAE Bedford where his many systems based programmes included control strategies for several fly-by-wire aircraft. He currently works in the Flight Test Department at Marshall Aerospace, Cambridge, mostly flying transport aircraft.

Date:	Config:	Overall Rating:	Pilot:

INITIAL OVERALL IMPRESSION

FEEL

Forces:

Displacements:

Sensitivity:

Trim:

APPROACH

Initial/Final response to control inputs:

Pitch attitude and flight path control:

Airspeed control:

Offset corrections: Vertical:

Lateral:

Special pilot technique:

FLARE AND TOUCHDOWN

Pitch attitude and flight path control:

Control of touchdown parameters:

Tendency to float:

Special pilot technique:

SUMMARY COMMENTS

Approach v's landing - which was most difficult:

Lateral directional characteristics a factor:

Good features:

Problems:

PILOT RATINGS

Approaches:

Flare and Touchdown:

Overall:

PIO:

Figure 12 Pilot Comment Card

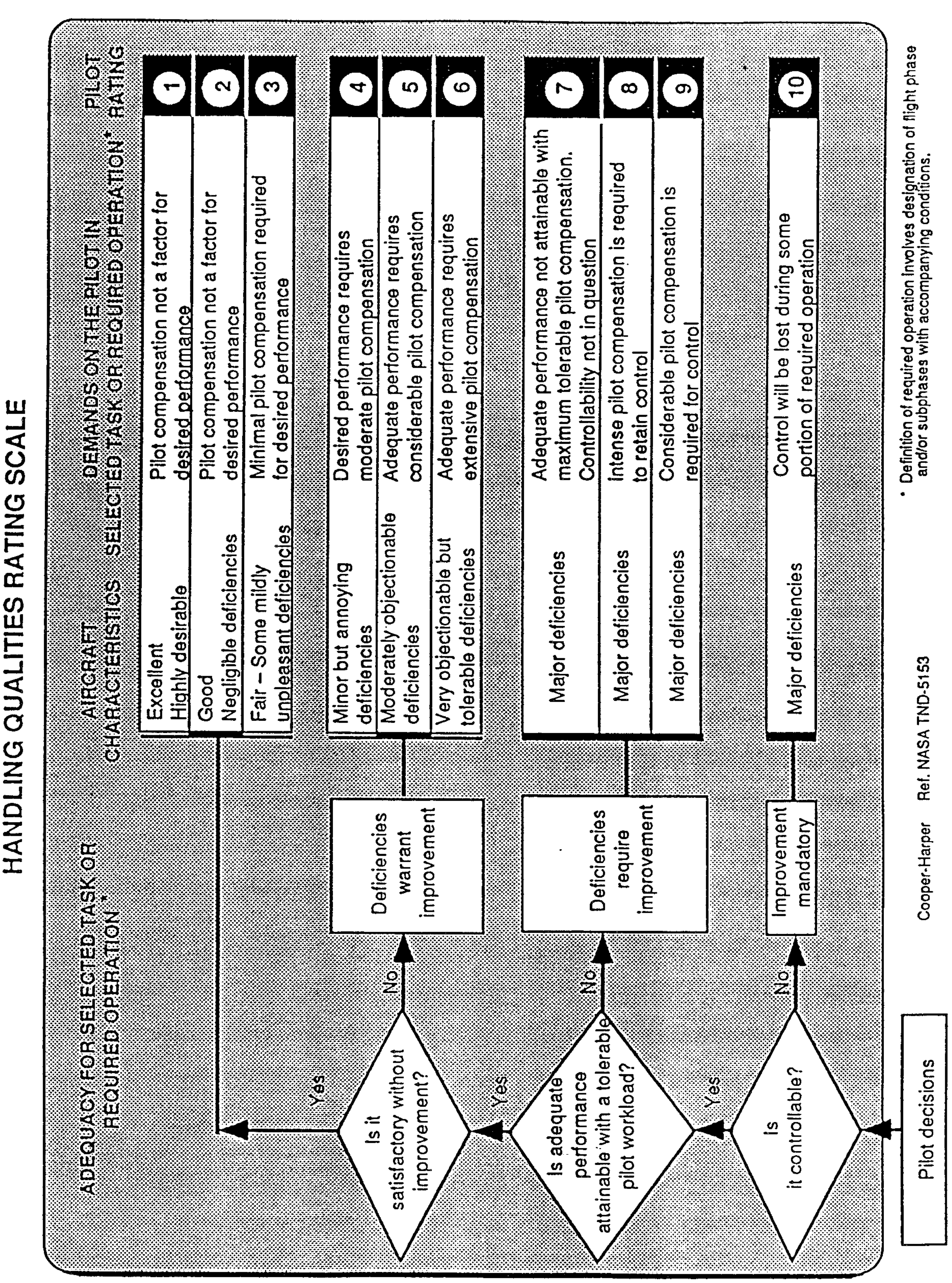


Figure 13 Cooper-Harper Handling Qualities Rating Scale

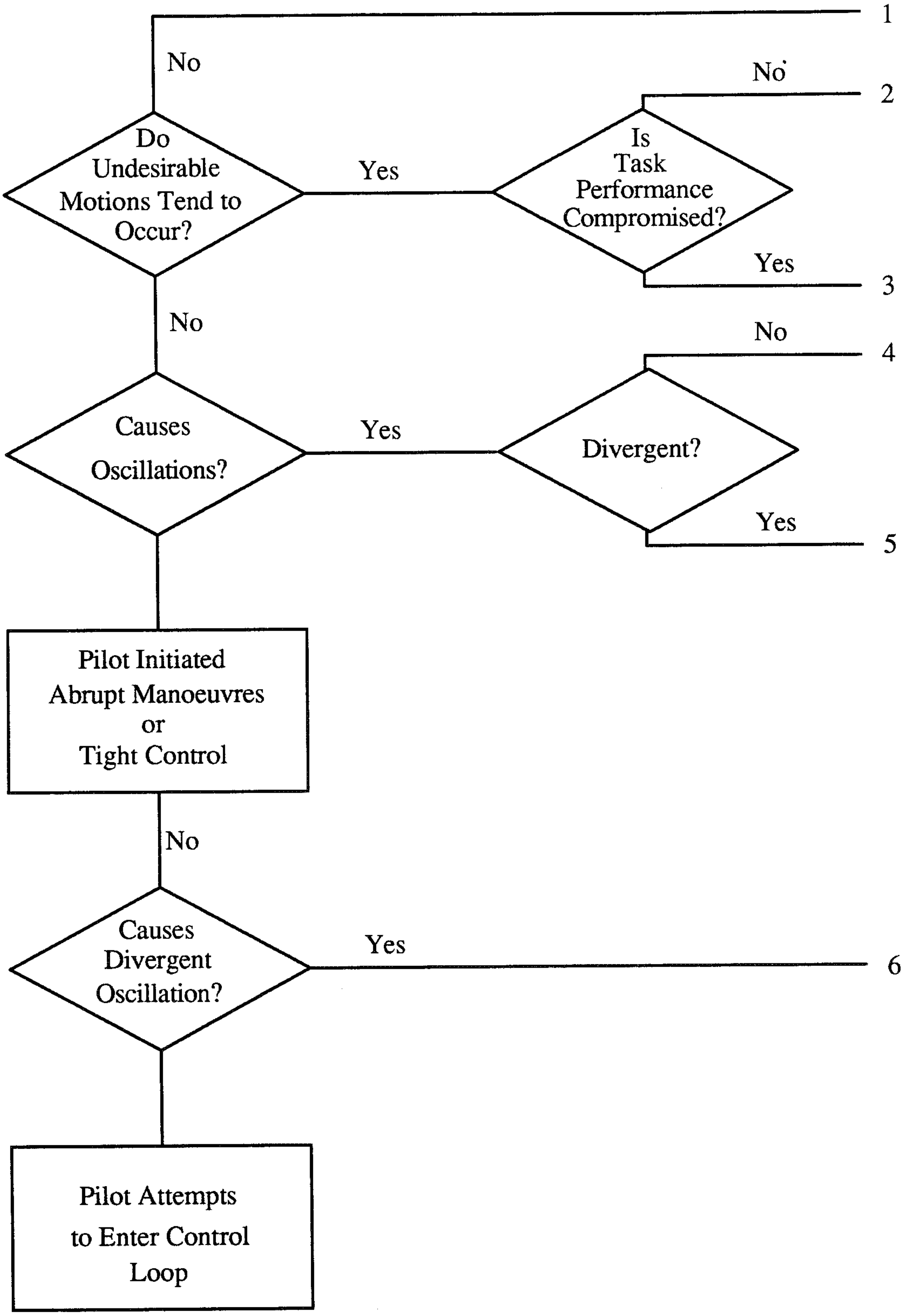


Figure 14 PIO Tendency Classification Scale

4.4 Evaluation Summary

In total 71 evaluations were made of 29 different configurations from 156 approaches, in six evaluation sessions. Pilot A evaluated all the control laws over three sessions, while the other pilots had one evaluation session each. As a result their evaluations concentrated on the datum mid CG and set P configurations. Additional evaluations of the other configurations would have been desirable, but were not possible due to time tabling constraints. Table 4 below gives a summary of the configurations, evaluations and approaches made by each pilot.

Pilot	Configurations	Evaluations	Approaches
A	29	35	81
B	12	14	29
C	12	14	29
D	7	8	17
Total	29	71	156

Table 4 Pilot Evaluation Summary

5. RESULTS

Because the analysis of the results of this investigation was limited to discussion no data was recorded on-line during the evaluations for later analysis. Data that was recorded was limited to touchdown point performance and Cooper-Harper and PIO ratings given by the evaluation pilots.

Summary data from the evaluations is given in tables 5 to 10. The following definitions apply to these tables:

Eval No: Evaluation number defined as X-Y-Z where:
X: Pilot
Y: Pilot's session number (1-3 for pilot A, 1 for all others)
Z: Evaluation number of the session.

Config: Control law configuration number.

ILS/Vis: ILS or Visual approach.

X: Longitudinal touchdown location in feet, measured from the start of the desired and adequate boxes, negative being short of the boxes.

Y: Lateral touchdown location in feet, negative left and positive right of centre line.

RoD: Rate of Descent at touchdown, in feet per second.

V: Touchdown speed in knots.

App: Cooper-Harper rating for the approach.

TD: Cooper-Harper rating for the flare and touchdown.

OV: Overall Cooper-Harper rating for the configuration.

PIO: PIO rating over the entire evaluation.

The evaluations were performed on the following dates:

Session Number	Date
A-1	29 October 1993
C-1	3 November 1993
A-2	5 November 1993, am
A-3	8 November 1993, am
B-1	8 November 1993, pm
D-1	12 November 1993, am

It was generally found that for the first few evaluations the pilots landed short due to unfamiliarity with the simulator and aircraft. Higher pilot position than that assumed and difficulty with judging attitude using external cues were noted, as well as the possibly excessive ground effect model. Undershoots recorded for the early ratings in tables 5 to 10 should therefore not be given undue prominence.

The results of several evaluations were dubious. These are marked with a "#" in tables 5 and 6. The dubious evaluations are:

A-1-2	As discussed in section 4.2 the evaluation pilot had calibrated himself to the unaugmented aircraft and as a result the first rating of the augmented configurations suffered. This can be seen in tables 11 to 14 where the rating given is clearly higher than that given in other evaluations of the same configuration. The results of the third evaluation, A-1-3, were not significantly different to the results from other evaluations and so it was decided that only A-1-2 should be discarded from the analysis.
C-1-11 to C-1-13	The pilot evaluating these configurations was recovering from influenza. It is believed that pilot fatigue towards the end of the session led to these receiving lower ratings than were given in other evaluations and so are excluded from primary analysis. The fault for this was the author's. Due to the limited evaluation time available there was a desire to evaluate as many configurations in each session as possible, leading to this problem.
C-1-14	This was the final evaluation of pilot C and so would be expected to suffer the same problems as the previous three. However the ratings given do not differ greatly from those given in other evaluations and so this rating is retained, although marked with an asterix in tables 11 to 14. The pilot was informed that this would be the final evaluation, and so it is likely that fatigue played a lesser role in this evaluation.

Pilot rating summaries are given in tables 11 to 14 for the approach, flare and touchdown, overall and PIO ratings respectively. Mean and median values for each control law are also given. The above dubious ratings appear in brackets in these tables and the mean and median values for these configurations are given in the tables both excluding and including these ratings, the values including these ratings being given in brackets.

Eval No	Config	ILS/Vis	X	Y	RoD	V	App	TD	OV	PIO
A-1-1	B-8	ILS	40	5	7	119	3	4	3	-
		Vis	145	5	6	120				
A-1-2	P-8-1	ILS	150	5	7	118	5	7	7	-
#		ILS	308	4	8	121				
		Vis	180	16	7	119				
A-1-3	P-8-2	ILS	5	5	8	121	4	7	7	-
		ILS	465	8	6	115				
		Vis	225	27	8	110				
		Hi Gain	820	-11	4	111				
A-1-4	P-8-4	ILS	220	2	6	118	2	4	4	-
		Vis	367	5	6	114				
A-1-5	P-8-3	ILS	30	4	5	119	3	3	3	-
		ILS	155	3	5	118				
		Vis	-80	5	6	116				
A-1-6	I-8-4	ILS	335	13	6	117	4	5	5	4
		Vis	100	10	5	114				
A-1-7	P-8-1	ILS	210	-1	5	116	3	4	4	3
		Vis	210	4	7	118				
		Vis	90	1	6	119				
A-1-8	P-8-14	ILS	80	-6	10	117	2	4	4	1
		ILS	105	11	7	118				
		Vis	250	7	4	117				
A-1-9	P-8-41	ILS	60	1	5	117	2	3	3	1
		Vis	200	14	6	115				

Table 5 Summary Evaluation Data - Session A-1

Eval No	Config	ILS/Vis	X	Y	RoD	V	App	TD	OV	PIO
C-1-1	P-8-4	ILS	-400	-2	10	125	5	5	5	2
		Vis	-200	-10	4	125				
C-1-2	P-8-5	ILS	-50	-7	8	122	4	4	4	1
		ILS	-200	17	4	123				
		Vis	200	-16	7	119				
C-1-3	P-8-3	ILS	250	14	1	122	3	3	3	2
		Vis	40	6	6	123				
C-1-4	P-8-2	ILS	80	3	11	124	9	9	9	1
		Vis	40	7	3	120				
C-1-5	P-8-1	ILS	137	7	4	122	3	2	3	1
		Vis	239	3	3	120				
C-1-6	P-8-6	ILS	681	7	5	117	5	7	6	1
		Vis	246	-1	5	122				
C-1-7	P-8-7	ILS	299	7	5	121	3	3	3	1
		Vis	346	8	4	119				
C-1-8	I-8-4	ILS	329	4	8	122	5	7	7	3
		Vis	455	-1	4	116				
C-1-9	P-8-14	ILS	263	4	3	120	3	3	3	1
		Vis	272	-2	3	117				
C-1-10	P-8-61	ILS	-247	5	6	124	7	10	10	1
		Vis	-410	-27	6	124				
C-1-11	P-8-41	ILS	215	16	6	121	8	8	8	1
#		Vis	-310	-4	2	124				
C-1-12	P-8-1	ILS	40	-1	7	122	6	6	6	2
#		Vis	-130	-5	1	122				
C-1-13	P-8-3	ILS	354	9	2	118	4	5	5	1
#		Vis	19	-16	6	122				
C-1-14	P-8-16	ILS	587	10	3	120	5	5	5	1
*		Vis	-50	-6	4	120				

Table 6 Summary Evaluation Data - Session C-1

Eval No	Config	ILS/Vis	X	Y	RoD	V	App	TD	OV	PIO
A-2-1	I-8-4	ILS	443	11	4	117	4	5	5	3
		ILS	230	1	1	120				
		Vis	442	-2	4	113				
A-2-2	I-8-4A	ILS	673	17	2	114	3	4½	4	1
		Vis	392	19	3	116				
		Vis	37	5	3	115				
A-2-3	P-8-4	ILS	302	5	4	118	3	5	4	1
		Vis	503	3	7	114				
A-2-4	P-8-16	ILS	139	4	5	118	3	3	3	1
		Vis	99	10	5	118				
A-2-5	P-8-61	ILS	-181	4	6	126	7	9	9	1
		Vis	-231	-5	6	121				
A-2-6	P-8-8	ILS	118	-5	4	118	3	4	4	2
		Vis	169	17	4	117				
A-2-7	P-8-1	ILS	274	12	4	116	2	2	2	1
		Vis	94	10	4	116				
A-2-8	P-8-5	ILS	137	-6	5	119	4	2	3	1
		Vis	60	3	5	117				
A-2-9	P-8-6	ILS	214	5	4	117	2	2	2	1
		Vis	110	15	4	116				
A-2-10	P-8-3	ILS	93	-1	4	119	2	3	2½	2
		Vis	-85	13	6	118				
		ILS	237	7	5	114				
A-2-11	P-8-7	ILS	186	-11	3	115	4	2	3	1
		Vis	222	8	3	115				
A-2-12	I-8-8	ILS	753	6	2	110	4	5	5	3
		Vis	-73	3	3	118				
A-2-13	I-8-8A	ILS	504	2	2	114	4	6	6	3
		Vis	117	8	4	113				

Table 7 Summary Evaluation Data - Session A-2

Eval No	Config	ILS/Vis	X	Y	RoD	V	App	TD	OV	PIO
A-3-1	I-8-6	ILS	344	-2	5	113	4	6	6	3
		Vis	634	4	2	111				
A-3-2	I-8-6A	ILS	330	2	4	113	5	6	6	4
		Vis	310	-6	2	114				
		ILS	555	19	6	112				
A-3-3	I-7-4	ILS	233	-10	7	117	3	4	4	2
		Vis	286	5	2	114				
A-3-4	P-7-4	ILS	203	2	3	115	2	3	3	1
		Vis	205	6	4	116				
A-3-5	I-7-4A	ILS	292	15	7	115	2	6	6	4
		Vis‡	891	16	6	109				
		ILS	189	2	4	113				
A-3-6	I-9-4A	ILS	361	7	4	114	4	6	5	4
		Vis	92.9	-1	5	116				
A-3-7	P-9-4	ILS	365	6	4	115	3	3	3	3
		Vis	224	10	3	117				
A-3-8	I-9-4	ILS	191	6	3	113	3	4	4	3
		Vis	580	-2	2	109				
A-3-9	P-7-1	ILS	203	-1	3	115	2	2	2	1
		Vis	166	-1	2	117				
A-3-10	P-9-1	ILS	35	9	5	116	2	2	2	1
		Vis	477	-2	4	115				
A-3-11	P-7-3	ILS	216	16	4	116	4	3	4	2
		Vis	251	-3	3	115				
A-3-12	P-9-3	ILS	149	-2	3	121	3	3	3	1
		Vis	480	11	2	114				
A-3-13	P-8-41	ILS	194	1	2	116	4	3	3	2
		Vis	190	7	4	119				

‡ Pilot completely open loop

Table 8 Summary Evaluation Data - Session A-3

Eval No	Config	ILS/Vis	X	Y	RoD	V	App	TD	OV	PIO
B-1-1	P-8-4	ILS	-181	-5	4	125	3	4	4	3
		ILS	8	-3	1	128				
		Vis	-207	-4	7	121				
B-1-2	P-8-5	ILS	237	-2	6	125	7	7	7	1
		Vis	110	-7	4	123				
B-1-3	P-8-2	ILS	98	-1	7	126	7	7	7	4
		Vis	-33	-3	5	123				
B-1-4	P-8-41	ILS	179	-7	6	121	5	5	5	3
		Vis	142	-3	5	122				
B-1-5	P-8-14	ILS	196	-3	6	122	2	3	3	1
		Vis	451	4	4	118				
B-1-6	P-8-1	ILS	47	-2	7	122	1	2	2	1
		Vis	312	-3	5	120				
B-1-7	P-8-6	ILS	848	9	5	118	3	6	5	1
		Vis	369	-3	2	119				
B-1-8	P-8-3	ILS	322	-5	4	123	3	5	4	1
		Vis	374	-7	3	120				
B-1-9	P-8-7	ILS	268	3	4	123	3	3	3	1
		Vis	187	-2	4	120				
B-1-10	P-8-16	ILS	311	4	3	121	4	5	4	2
		Vis	352	-2	3	120				
B-1-11	P-8-8	ILS	415	7	3	119	3	5	5	2
		Vis	624	1	2	117				
B-1-12	I-8-4A	ILS	878	0	4	117	5	8	8	4
		Vis	815	2	3	119				
B-1-13	P-8-5	ILS	225	-5	4	121	7	7	7	1
		Vis	286	2	4	118				
B-1-14	P-8-3	ILS	206	-4	5	120	4	3	3	1
		Vis	130	1	5	122				

Table 9 Summary Evaluation Data - Session B-1

Eval No	Config	ILS/Vis	X	Y	RoD	V	App	TD	OV	PIO
D-1-1	P-8-4	ILS	Data	Not	Reco	rded	2	3	3	2
		Vis								
D-1-2	P-8-5	ILS	389	14	7	110	4	4	4	1
		ILS	4	-1	4	117				
		Vis	430	7	4	115				
D-1-3	P-8-2	ILS	234	6	7	117	6	6	6	4
		Vis	237	-2	7	115				
D-1-4	P-8-3	ILS	145	-3	7	122	1	2	2	1
		Vis	81	8	3	116				
D-1-5	P-8-6	ILS	443	12	7	121	3	5	5	1
		Vis	163	20	3	119				
D-1-6	P-8-1	ILS	435	7	4	120	3	3	3	1
		Vis	125	3	5	118				
D-1-7	P-8-4	ILS	268	4	6	120	5	5	5	1
		Vis	188	-5	6	118				
D-1-8	P-8-7	ILS	212	9	5	118	4	3	4	2
		Vis	143	2	7	115				

Table 10 Summary Evaluation Data - Session D-1

Configuration	A	B	C	D	Mean	Median
B-8	3				3 .	3
P-8-1	(5), 3, 2	1	3, (6)	3	2.4, (3.3)	3, (3)
P-8-2	4	7	9	6	6.5	6.5
P-8-3	3, 2	3, 4	3, (4)	1	2.7, (2.9)	3, (3)
P-8-4	2, 3	3	5	2, 5	3.3	3
P-8-5	4	7, 7	4	4	5.2	4
P-8-6	2	3	5	3	3.3	3
P-8-7	4	3	3	4	3.5	3.5
P-8-8	3	3			3	3
P-8-14	2	2	3		2.3	2
P-8-16	3	4	5*		4	4
P-8-41	2, 4	5	(8)		3.7, (4.8)	4 , (4.5)
P-8-61	7		7		7	7
I-8-4	4, 4		5		4.3	4
I-8-4A	3	5			4	4
I-8-6	4				4	4
I-8-6A	5				5	5
I-8-8	4				4	4
I-8-8A	4				4	4
P-7-1	2				2	2
P-7-3	4				4	4
P-7-4	2				2	2
I-7-4	3				3	3
I-7-4A	2				2	2
P-9-1	2				2	2
P-9-3	3				3	3
P-9-4	3				3	3
I-9-4	3				3	3
I-9-4A	4				4	4

Table 11 Pilots Ratings Summary - Approach

Configuration	A	B	C	D	Mean	Median
B-8	4				4	4
P-8-1	(7), 4, 2	2	2, (6)	3	2.6, (3.7)	2, (3)
P-8-2	7	7	9	6	7.3	7
P-8-3	3, 3	5, 3	3, (5)	2	3.2, (3.4)	3, (3)
P-8-4	4, 5	4	5	3, 5	4.3	4.5
P-8-5	2	7, 7	4	4	4.8	4
P-8-6	2	6	7	5	5	5.5
P-8-7	2	3	3	3	2.8	3
P-8-8	4	5			4.5	4.5
P-8-14	4	3	3		3.3	3
P-8-16	3	5	5*		4.3	5
P-8-41	3, 3	5	(8)		3.7, (4.8)	3, (4)
P-8-61	9		10		9.5	9.5
I-8-4	5, 5		7		5.7	5
I-8-4A	4½	8			6.3	6.3
I-8-6	6				6	6
I-8-6A	6				6	6
I-8-8	5				5	5
I-8-8A	6				6	6
P-7-1	2				2	2
P-7-3	3				3	3
P-7-4	3				3	3
I-7-4	4				4	4
I-7-4A	6				6	6
P-9-1	2				2	2
P-9-3	3				3	3
P-9-4	3				3	3
I-9-4	4				4	4
I-9-4A	6				6	6

Table 12 Pilots Ratings Summary - Flare and Touchdown

Configuration	A	B	C	D	Mean	Median
B-8	3				3	3
P-8-1	(7), 4, 2	2	3, (6)	3	2.8, (3.9)	3, (3)
P-8-2	7	7	9	6	7.3	7
P-8-3	3, 2½	4, 3	3, (5)	2	2.9, (3.2)	3, (3)
P-8-4	4, 4	4	5	3, 5	4.2	4
P-8-5	3	7, 7	4	4	5	4
P-8-6	2	5	6	5	4.5	5
P-8-7	3	3	3	4	3.3	3
P-8-8	4	5			4.5	4.5
P-8-14	4	3	3		3.3	3
P-8-16	3	4	5*		4	4
P-8-41	3, 3	5	(8)		3.7, (4.8)	3, (4)
P-8-61	9		10		9.5	9.5
I-8-4	5, 5		7		5.7	5
I-8-4A	4	8			6	6
I-8-6	6				6	6
I-8-6A	6				6	6
I-8-8	5				5	5
I-8-8A	6				6	6
P-7-1	2				2	2
P-7-3	4				2	2
P-7-4	3				3	3
I-7-4	4				4	4
I-7-4A	6				6	6
P-9-1	2				2	2
P-9-3	3				3	3
P-9-4	3				3	3
I-9-4	4				4	4
I-9-4A	5				5	5

Table 13 Pilots Ratings Summary - Overall

Configuration	A	B	C	D	Mean	Median
B-8	-					
P-8-1	-, 3, 1	1	1, (2)	1	1.4, (1.3)	1, (1)
P-8-2	-	4	1	4	3	4
P-8-3	-, 2	1, 1	2, (1)	1	1.4, (1.3)	1, (1)
P-8-4	-, 1	3	2	2, 1	1.8	2
P-8-5	1	1, 1	1	1	1	1
P-8-6	1	1	1	1	1	1
P-8-7	1	1	1	2	1.3	1
P-8-8	2	2			2	2
P-8-14	1	1	1		1	1
P-8-16	1	2	1*		1.3	1
P-8-41	1, 2	3	(1)		2, (1.8)	2, (1.5)
P-8-61	1		1		1	1
I-8-4	4, 3		3		3.3	3
I-8-4A	1	4			2.5	2.5
I-8-6	3				3	3
I-8-6A	4				4	4
I-8-8	3				3	3
I-8-8A	3				3	3
P-7-1	1				1	1
P-7-3	2				2	2
P-7-4	1				1	1
I-7-4	2				2	2
I-7-4A	4				4	4
P-9-1	1				1	1
P-9-3	1				1	1
P-9-4	3				3	3
I-9-4	3				3	3
I-9-4A	4				4	4

Table 14 Pilots Ratings Summary - PIO

Cooper-Harper Rating Charts

Pilot Cooper-Harper ratings are presented schematically in figures 15 to 23, excluding the dubious ratings.

Key

Pilot	
A	■
B	□
C	●
D	○
Median	◆

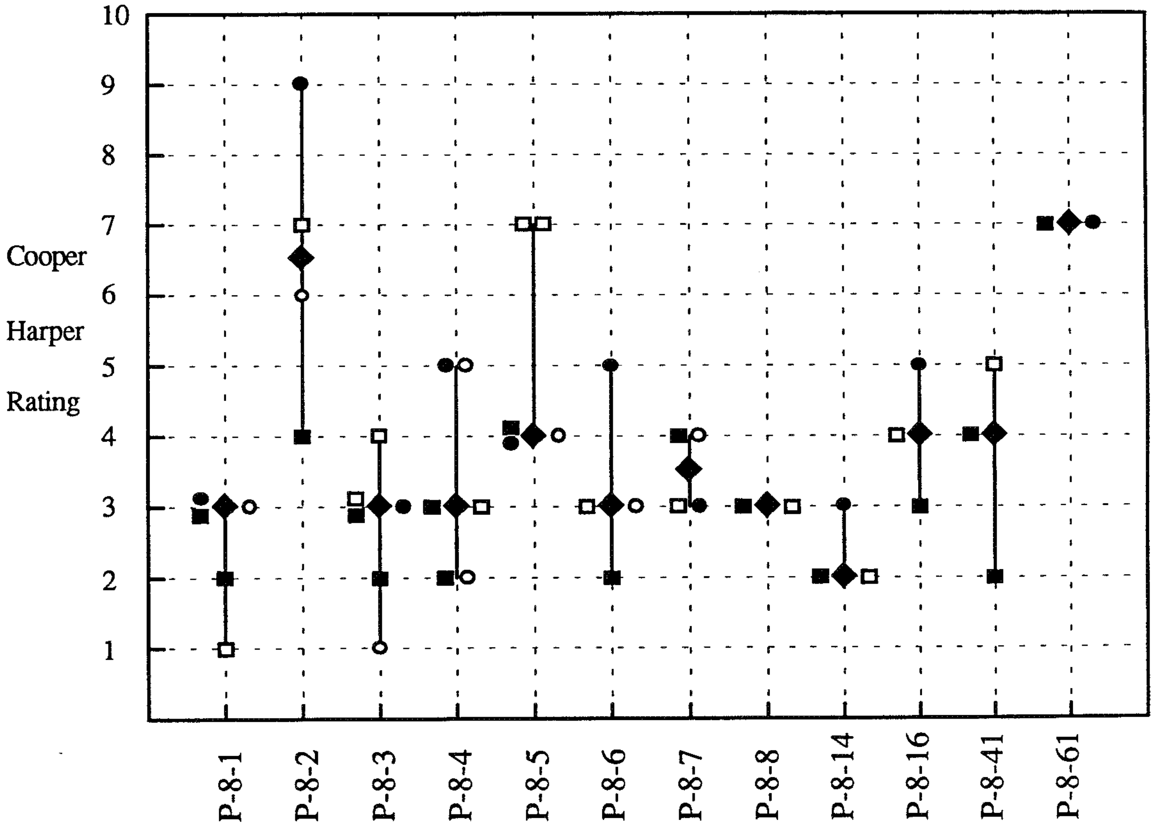


Figure 15 Configuration P-8 Cooper-Harper Ratings - Approach

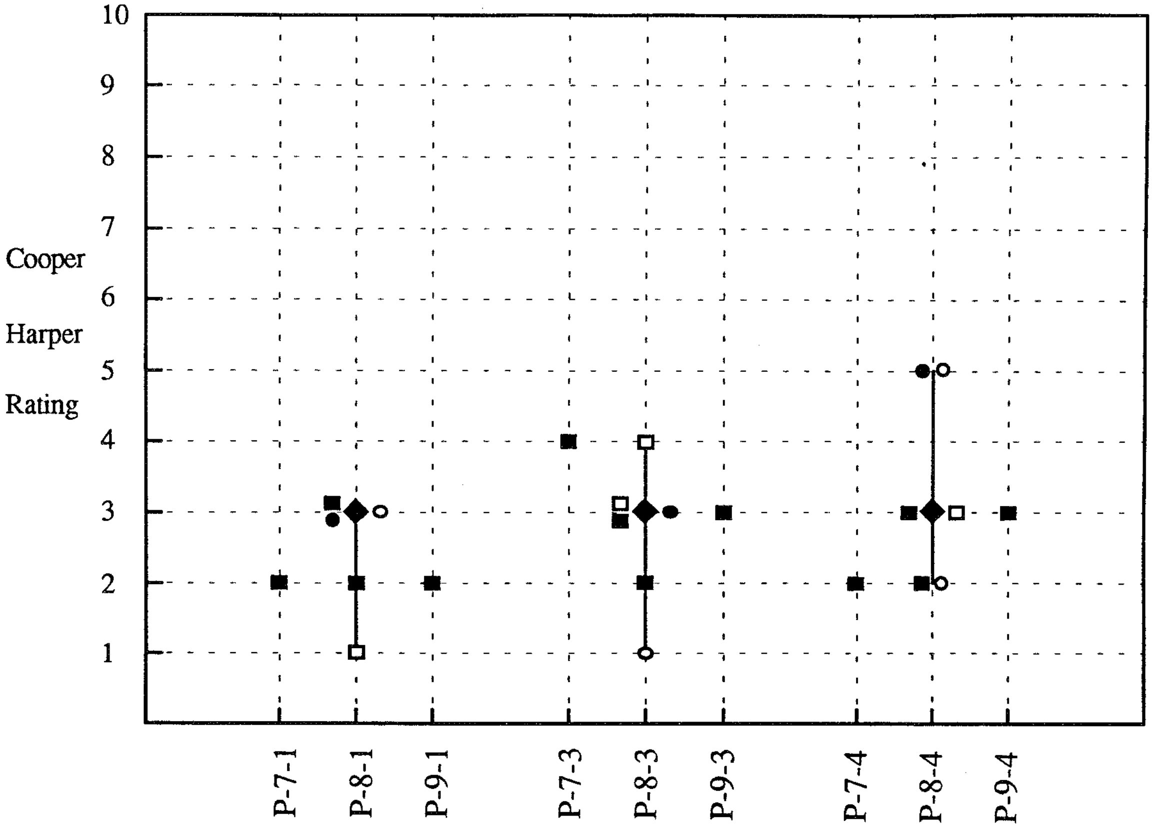


Figure 16 Configuration P-7/8/9 Cooper-Harper Ratings - Approach

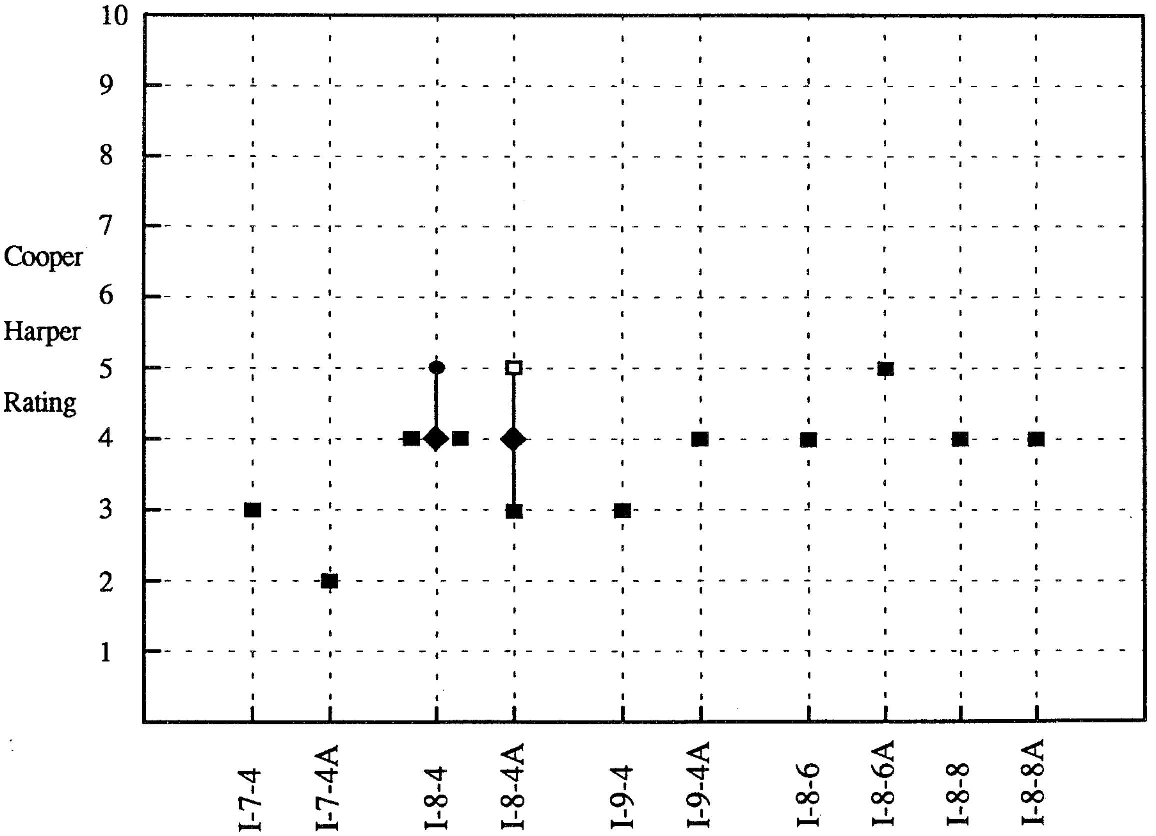


Figure 17 Set I Cooper-Harper Ratings - Approach

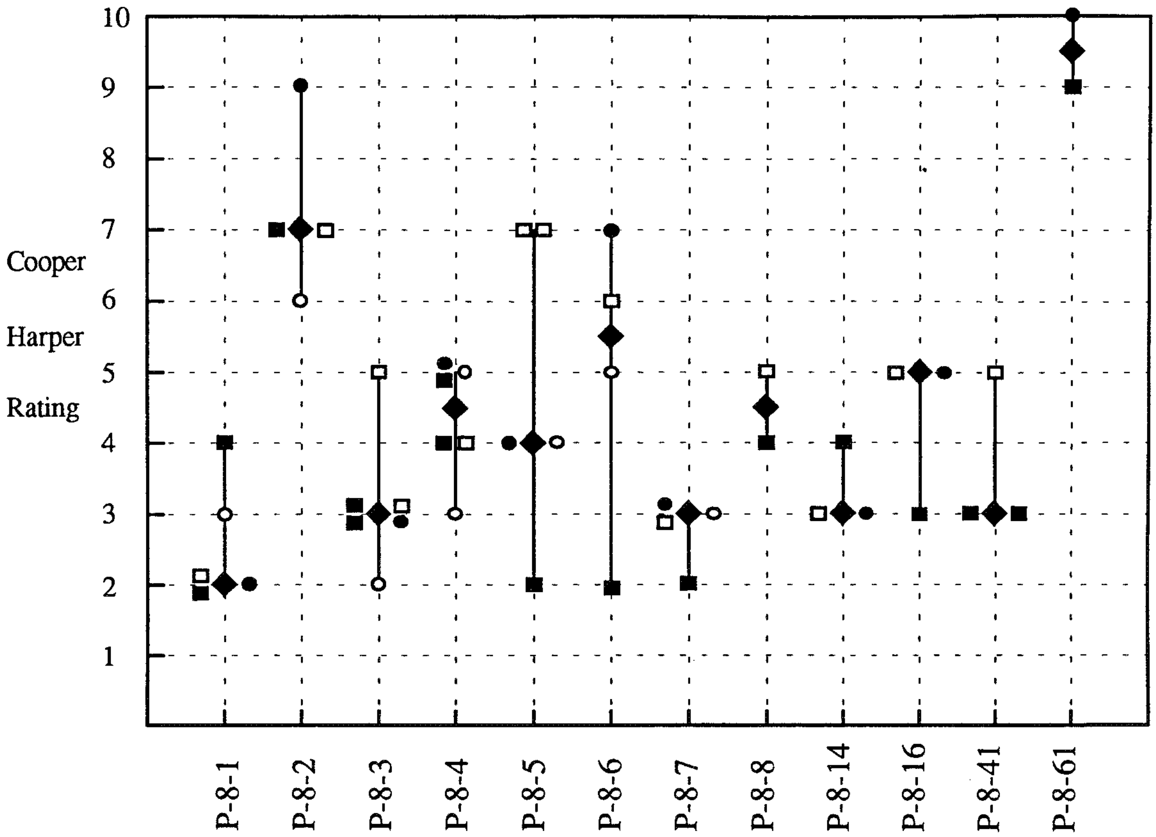


Figure 18 Configuration P-8 Cooper-Harper Ratings - Flare and Touchdown

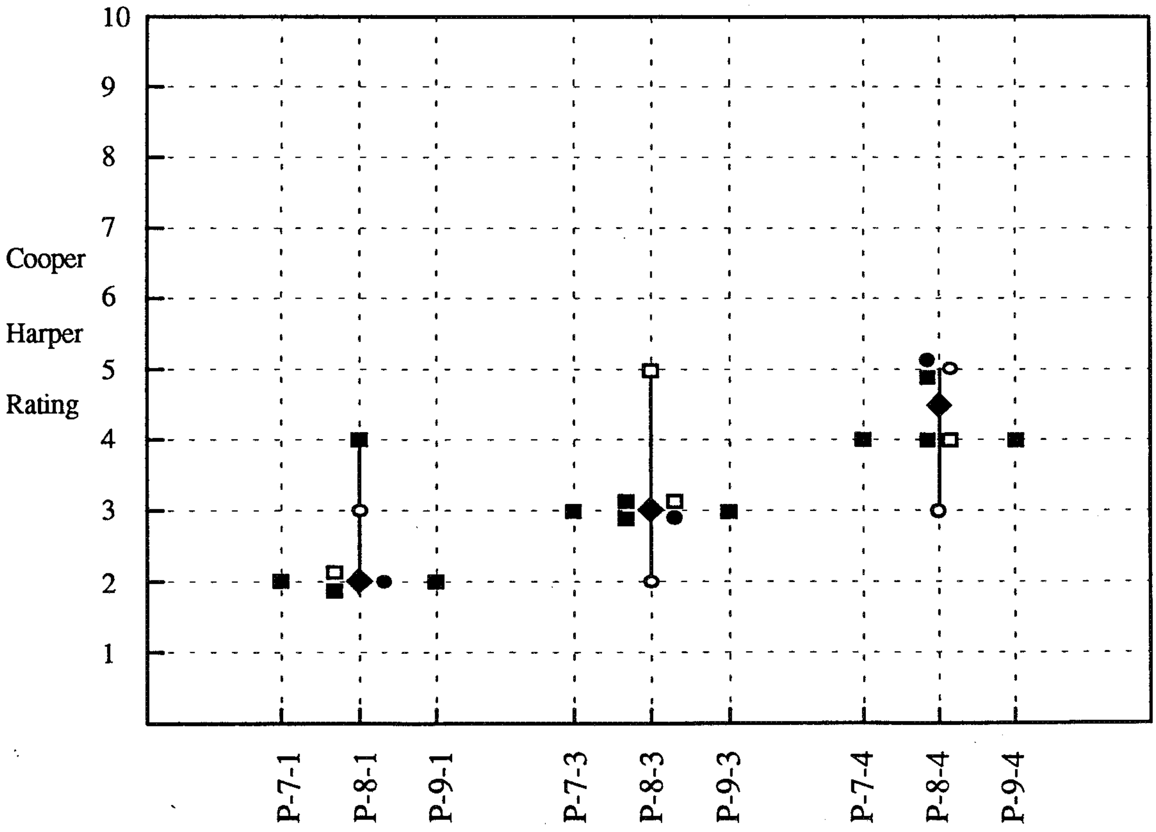


Figure 19 Configuration P-7/8/9 Cooper-Harper Ratings - Flare and Touchdown

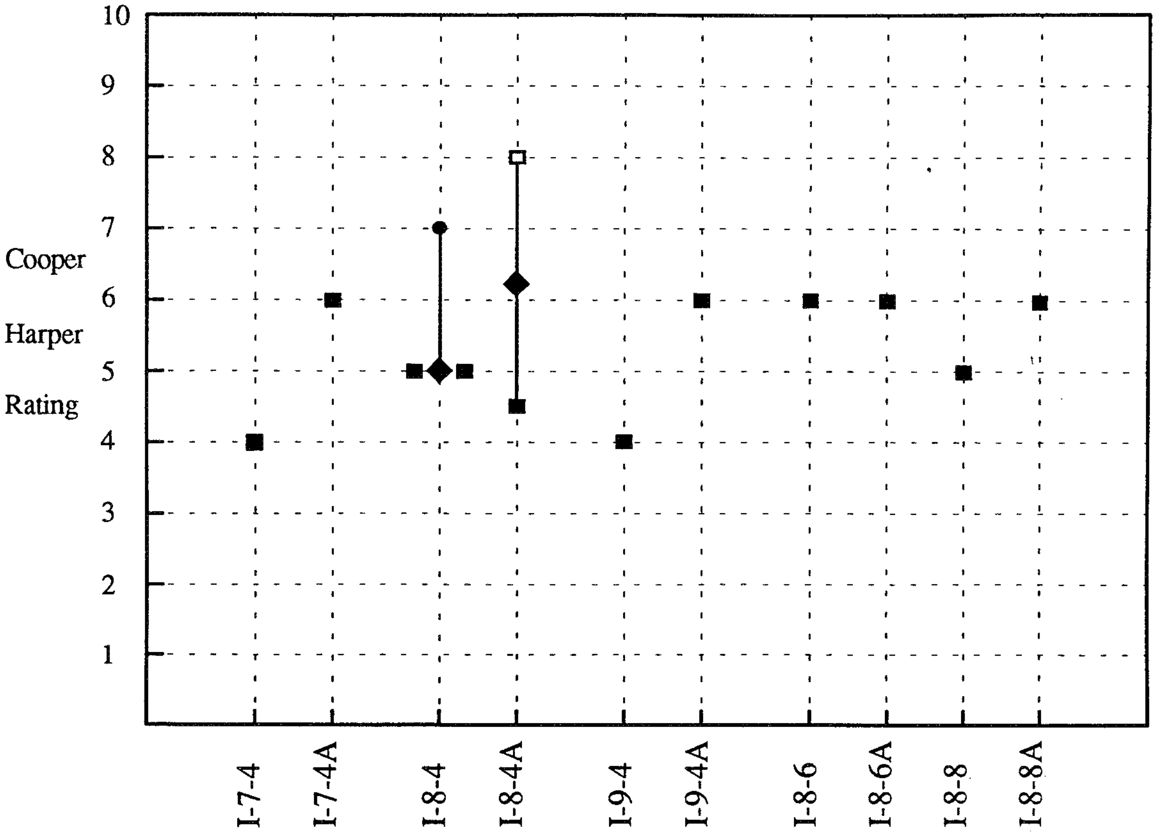


Figure 20 Set I Cooper-Harper Ratings - Flare and Touchdown

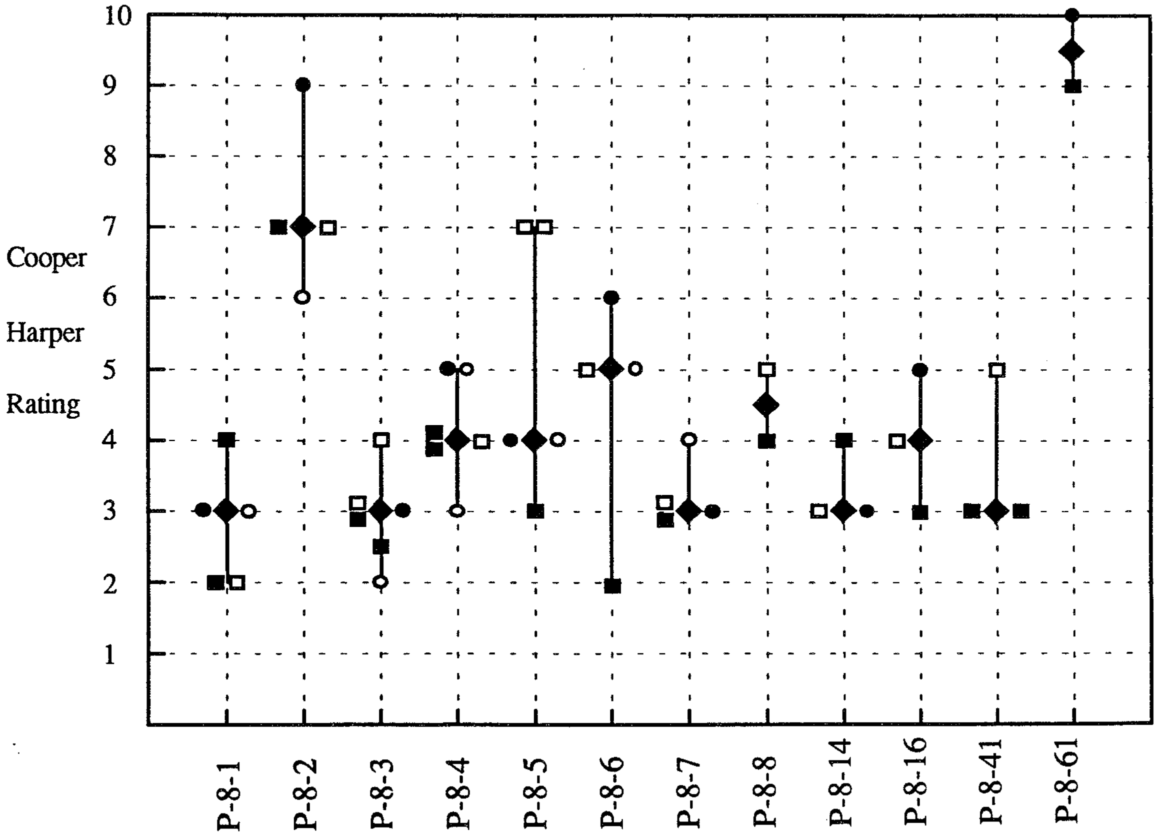


Figure 21 Configuration P-8 Cooper-Harper Ratings - Overall

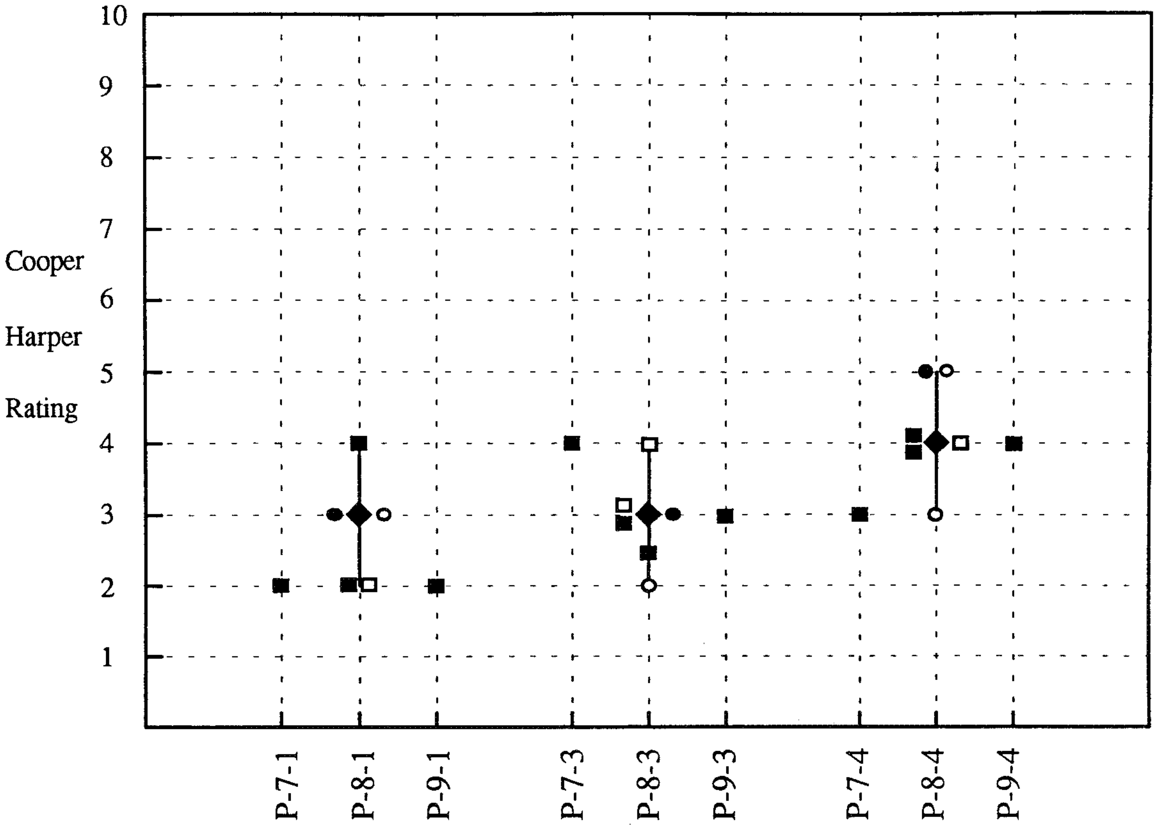


Figure 22 Configuration P-7/8/9 Cooper-Harper Ratings - Overall

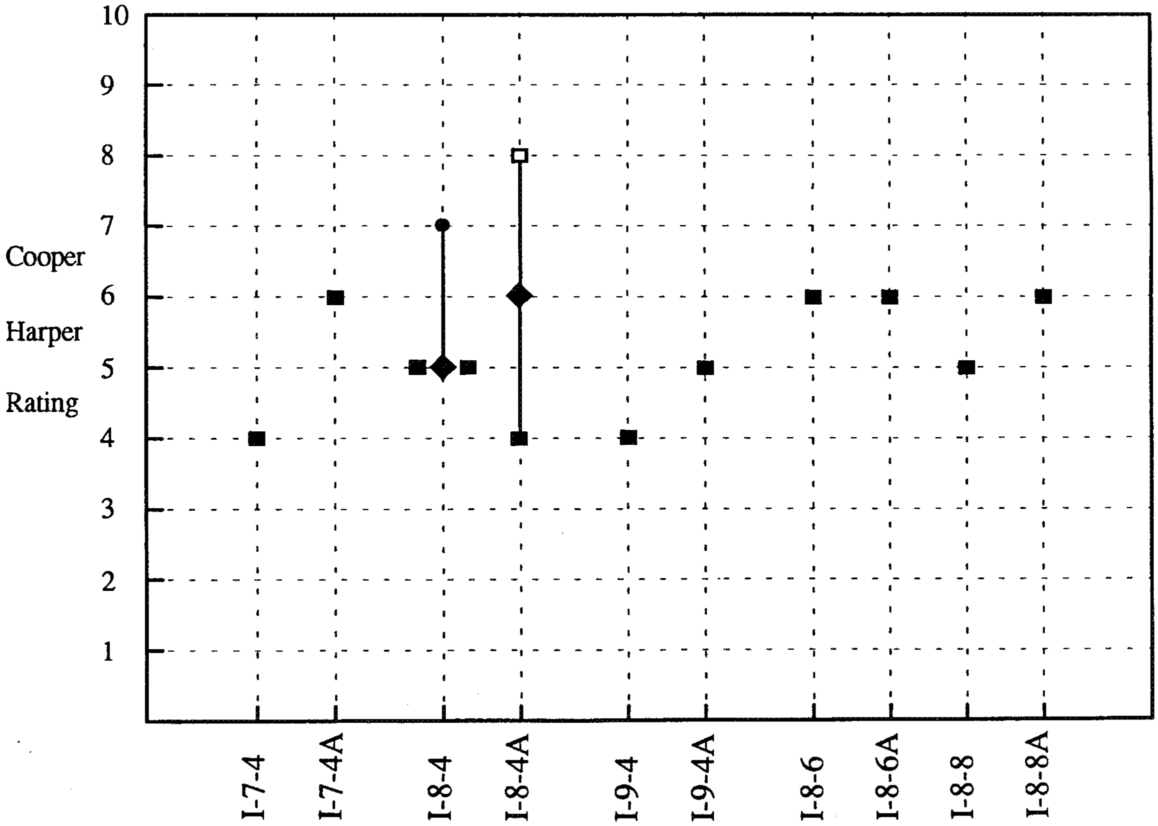


Figure 23 Set I Cooper-Harper Ratings - Overall

6. DISCUSSION OF RESULTS

The analysis of the results from this investigation is limited to a qualitative discussion at this stage. Studies such as that reported in references 1 to 3 have used their results to test existing design and evaluation criteria and to develop new ones. It is felt that this approach is not applicable at this stage with the results from this investigation.

There are two main reasons for this, firstly the fidelity of the simulation, as discussed in section 6.1, and secondly concerns about the results of ground simulator investigations compared to those of in-flight simulators.

Criteria developed with insufficient verification by in-flight simulation have been shown to be deficient when tested with data from in-flight simulations, references 15 and 17 for example. One reason for this is that the task in a ground simulator is not so critical and therefore not so high gain. Additionally the cues on landing to a pilot in a ground simulator are poor compared to those in an in-flight simulator, reference 6. Therefore a ground simulator is poor for development or assessment of control laws for the flare.

Therefore it was decided to limit the analysis of the results from this investigation to a qualitative discussion.

6.1 Limitations of the Evaluations

There are several limitations of the evaluations which will have had an effect upon the results of the investigation. These fall into two main categories, those associated with the simulator, and simulated aircraft model, and those associated with the implementation of the evaluation.

The majority of the characteristics of the engineering simulator and simulated aircraft model were fixed and so were not variables of this investigation. Some of these features did lead to problems, many of which have already been identified.

The lateral flying qualities of the simulator were a definite factor in the evaluations and were the cause for reducing the lateral offset from 200 feet to 100 feet from the runway centreline. The most likely cause for this was the oversensitivity of the direct roll control system used in the simulator, coupled with the lack of motion cues, and not the basic handling qualities of the aircraft, however this problem did affect the evaluations.

The ability of any ground simulator to accurately reproduce high fidelity landing cues to a pilot is limited. Boeing, reference 6, found the landing task in an in-flight simulator to be higher gain than that of holding a precise altitude close to the ground. Comparing their results to those of an earlier ground simulation investigation they also concluded that flare and touchdown tasks can only be truly evaluated in-flight with an approach continued to touchdown. The additional visual cues and real life anxiety are required to get the required pilot gain.

Identification of a floating tendency can be difficult in a ground simulator. One pilot in particular seldom noted an overt floating tendency however did note that he was using a sampling technique in the flare for configurations which other pilots reported exhibited a tendency to float. As a result sampling in the flare for this pilot was taken as an indication of a floating tendency. It is likely that identification of this tendency would have been more obvious in an in-flight simulator. Another factor that is likely to have masked the floating tendency was the ground effect model. This model was considered to be a little severe in its nose down pitching effect upon the aircraft as it came close to the ground. This argument is supported by pilots reporting an unexpected ground rush on their initial evaluations. As a result there was a need to counteract this with a back force for all configurations.

Possibly the greatest limitation of the investigation was the decision to retain the unaugmented aircraft's basic modal properties for the augmented configurations. This produced problems due to the lightly damped and slow short period response, resulting in all configurations being somewhat sensitive. The commanded responses of the angle command systems was oscillatory due to the second order like response with several overshoots due to the low damping, appendix B. With higher damping the responses would have been less oscillatory. The set P rate command systems gave first order like commanded responses and were less sensitive, although still slow to respond, appendix B. With the set I configurations the under damped oscillatory second order like commanded responses, similar to those of the set P angle command systems, were restored resulting in a very sensitive oscillatory rate response, appendix C. Had the short period frequency and damping been better chosen then the results for some of the configurations would almost certainly have been different, in particular the set I configurations would probably have been rated better.

The remainder of the limitations concern the implementation of the evaluations. The lack of pre-evaluation calibration meant that the configurations being evaluated did not all give the responses as desired. For most configurations the responses were reasonable, the two main exceptions being P-8-5 and P-8-61. However calibration would have allowed command gain changes to ensure that all the configurations were more similar in their force requirements. Part of the problem for this was due to working at a distance from the simulator and the limited availability of both the facility and pilots. As discussed in section 3.7 further definition of the sensitivity for pitch attitude and flight path command systems is required. However these problems did not greatly affect the results of the evaluations.

The control laws were designed for only one speed and aircraft configuration. It may have been desirable to consider flight path control and trimming requirements with changes in configuration and speed. This would have been predominately for the approach phase and would have allowed better correlation with the work of Boeing and Fokker, references 10 and 14.

Similarly the configurations were designed for the small perturbations model, however were evaluated on the full simulation model. As a result there were differences between the designed and evaluated responses.

It is also considered that the evaluation sequence was not tough enough to expose possible deficiencies in some of the configurations. This being a preliminary investigation it was decided to limit the scope of the test and simplify it somewhat from the established evaluation sequences of other investigations, and so no atmospheric disturbances were included in the evaluation sequence. As a result those configurations which would have exhibited poorer turbulence response were not directly identified in this preliminary investigation. Although they may have been indirectly identified in the pilot comments, they are generally not taken account of in the ratings given.

The decision not to include atmospheric disturbances in the evaluation sequence did have a benefit for the flight path angle and rate command systems. It is accepted that these systems require an auto-throttle to accurately maintain speed in order to avoid over active elevator movement, associated with manual speed control, through atmospheric disturbances, which may result in the aircraft stalling. Since no auto-throttle was available for the evaluations the lack of modelled atmospheric disturbances saved the problems above. Further, since the primary purpose of this investigation was a comparison of different command concepts it is correct that the same evaluation technique was used for all configurations.

The final factor affecting the results was the length of the evaluation sessions. Due to the limited number of sessions there was a desire to perform as many evaluations per session as possible. This however led to problems towards the end of long sessions of overload and difficulty in separating the observations of one configuration from another. At the other extreme it took several evaluations to become familiar with the basic aircraft, simulator and evaluation sequence. The ideal would have been sessions of half a day per pilot with a break, away from the simulator, mid way through the session. This would have allowed around ten configurations to be evaluated per session. In reality the pressure to perform as many evaluations as possible led to slightly more than this on most occasions, and also led to the problems of session C-1.

6.2 Set P Configurations

The following discussions concern the set P configurations on a control law by control law basis. Performance measurements and Cooper-Harper ratings for the control laws are given in tables 5 to 13 and figures 15, 16, 18, 19, 21 and 22.

P-8-1 α command

The overall median rating of 3 for this configuration was the highest achieved, although shared with several other configurations. For the flare and touchdown it received the best median rating of all configurations, a 2, and in the approach pilot D gave it a rating of 1.

All pilots found it to be predictable and conventional with minimal, if any, trimming required. Airspeed control was not a problem.

It did however receive two poor ratings which were discarded, as discussed in section 5. The reasons for these ratings, other than already discussed, was due to the slow and under damped response, a feature of the unaugmented aircraft. These complaints were made throughout the evaluations, especially of the angle command systems, and so will not be considered further in this section.

P-8-2 $\dot{\alpha}$ command

With the exception of configuration P-8-61 this configuration received the worst rating in all categories. It was found to be unpredictable and lacked longitudinal stability, contributing to it being difficult to hold airspeed. It was far too sensitive, PIO prone and floated, or as one pilot noted "more a tendency to loop". All pilots used a sampling technique to retain control.

P-8-3 θ command

This configuration received median ratings of 3 for all categories and even received a rating of 1 in the approach from one pilot. It was found to be positive, precise and predictable. It was considered conventional except for the need to trim to a new attitude. Some pilots liked the attitude, and perceived flight path, stability, although pilot B was less happy with the forces and requirement to re-trim to a new attitude, and down rated it accordingly. Speed control was no problem, however a possible slight tendency to float was noted by some pilots, as was found in reference 13.

P-8-4 q command

The median ratings for this configuration were 3 in the approach, 4½ in the flare and 4 overall. Although noted for being reasonably conventional the response was found to be not entirely predictable, as well as being over sensitive the attitude response appeared a little oscillatory with the pilots having to damp this out. A high workload, low gain sampling technique was used to avoid PIOs and achieve what was desired. The configuration lacked positive response and airspeed control was a problem. A floating tendency was noted.

P-8-5 γ_{cg} command

This configuration suffered a suspected implementation problem in that the stick forces were excessively high, section 3.7. This coloured the pilots' overall impression, however it was noted that it held flight path very well and that if the forces were lower then the pilots would have preferred it. Pilot B in particular disliked the excessive forces and rated it 7 for all categories on two separate evaluations. Median values of 4 reflected the other pilots impressions, with pilot A giving it a 2 in the flare and touchdown, here the positive forces were considered a good feature. The configuration showed no tendency to float and airspeed control was no problem.

P-8-6 $\dot{\gamma}_{cg}$ command

Pilot A rated this configuration considerably better than the others, ratings of 2 for all categories as opposed to median ratings of 3 for the approach, 5½ for the flare and touchdown and 5 overall. Generally it was found to be flight path stable on the approach with no need to trim and could be flown hands off, however flight path control in the flare was a problem with a definite floating tendency noted. Airspeed control was also a problem.

P-8-7 γ_p command

Median ratings for this configuration were 3½ for the approach, 3 for the flare and touchdown and 3 overall. It was found to be predictable and gave good control of flight path. However the requirement to trim to a new flight path, about 6 seconds of trim, was found to be a little obtrusive and unnatural. Operating around trim was no problem, but manoeuvring away from trim required high forces. Forces in the flare were described as "between reasonable and slightly heavy", with no tendency to float. Airspeed control was not a problem.

P-8-8 $\dot{\gamma}_p$ command

This configuration was pleasant in the approach with good flight path control, no requirement to trim and light forces, median rating of 3, although airspeed control was poor. In the flare and touchdown it was found to be over sensitive requiring a sampling technique to avoid over rotating and floating, hence the median rating of 4½ both for flare and touchdown and overall.

P-8-14 α short term, q long term

This configuration achieved median ratings of 3 for the flare and touchdown and overall and a median rating of 2 for the approach. Generally it felt conventional and predictable however the pilots did notice a tendency to bob about a bit in pitch. The pilots were not aware of a tendency for floating, however did report a reluctance to over rotate and a need to sample in the flare, features which were associated with floating configurations in other evaluations. Pilot C concluded "this configuration comes out better than it should have, there was something there that I wasn't happy with".

P-8-16 α short term, $\dot{\gamma}_{cg}$ long term

Predictability was a problem with this configuration, a tendency to overshoot the desired correction was noted, although so was good flight path control. No trimming was required and airspeed control caused some problems. Sampling in the flare and a floating tendency were observed. The median ratings reflect these issues with a 4 for approach, 5 for flare and touchdown and a 4 overall.

P-8-41 q short term, α long term

The pilots found the forces on the approach were light and moderate in the flare. Generally it felt conventional and predictable with a need to trim. Airspeed control was not a problem and there was no tendency to float, with moderate forces in the flare noted as a good feature. Median ratings were 4 for the approach, 3 for flare and touchdown and 3 overall.

P-8-61 $\dot{\gamma}_{cg}$ short term, α long term

This configuration was the only one to receive a rating of 10. It is believed that this is not due to the concept, but to the implementation, as reported in section 3.7. The forces were excessive, trim authority exceeded, and there was insufficient control authority to flare the aircraft. This configuration would have been modified had pre-evaluation calibration been possible, however the results must be discarded since it is believed that the ratings are not representative of the concept.

P-7-1 and P-9-1 α command

Both these configurations were found to be predictable and conventional in feel. Positive forces in the flare were accompanied by no floating tendency, flight path and attitude control were good. Ratings for all categories were 2 for both configurations, compared to a 3 for approach and overall for P-8-1 and a 2 for the flare and touchdown. These two configurations support the ratings given to P-8-1.

P-7-3 and P-9-3 θ command

P-7-3 was rated slightly worse with 4s for the approach and overall, while P-9-3 received ratings of 3 for all categories, as did P-8-3. The forces were objected to for the forward CG case, although this was likely to be within the limits of experimental error, rather than due to the effect of the forward CG. For P-7-3 and P-9-3 no floating tendency was noted and P-9-3 was liked for the meaty forces required in the flare.

P-7-4 and P-9-4 q command

These configurations were found to be fairly conventional in the approach where they received ratings of 2 and 3 respectively, however P-9-4 was found to be more sensitive. No direct floating was noted, however light forces and sampling in the flare suggest a floating tendency. Ratings of 4 were given for both in the flare and touchdown, confirming the unsatisfactory control in this phase.

6.3 Set I Configurations

The following discussions concern the set I configurations on a control law by control law basis. Performance measurements and Cooper-Harper ratings for the control laws are given in tables 5 to 13 and figures 17, 20 and 23.

I-8-4 q command

This configuration was definitely found to be very sensitive and predictability was low. The pilots tended to use a low gain sampling technique and airspeed control was found to be a problem. It was found to be responsive for flying the flight director, however difficult on the visual approach to control the flight path. It definitely floated. Median ratings were 4 for the approach 5 for the flare and touchdown and overall.

I-8-4A q command

Pilot A preferred this configuration to I-8-4, however the median ratings were the same in the approach and one point poorer for the other categories. Otherwise it was much the same as I-8-4, a definite floater.

I-8-6 $\dot{\gamma}_{cg}$ command

This configuration was described as moderately unpleasant, predictability in the approach was moderate, pitch attitude and flight path control were poor, leading to an approach rating of 4. Pitch attitude and flight path control in the flare was also poor and the configuration was a definite floater, resulting in a flare and touchdown rating of 6, also rated 6 overall.

I-8-6A $\dot{\gamma}_{cg}$ command

Comments on this configuration were almost identical to those of I-8-6, additional comments concerned the low gain pilot technique employed. The only rating difference was in the flare, where this configuration received a 5.

I-8-8 $\dot{\gamma}_p$ command

This was noted to be a little sensitive, however reasonably predictable with pretty good pitch attitude and flight path control in the approach giving a rating of 4. There was a tendency to over rotate and a definite floating tendency leading to a rating for the flare and touchdown of 5, as well as 5 overall.

I-8-8A $\dot{\gamma}_p$ command

This configuration was found to be more sensitive than I-8-8, predictability was lower however the approach rating of 4 was the same. There was a definite tendency to over control resulting in a need to keep the pilot gain low and a definite floater. Flare and touchdown and overall ratings were 6.

I-7-4, I-7-4A, I-9-4 and I-9-4A *q* command

These configurations were similar to those for the mid CG loading case, sensitive, poor predictability, slightly unconventional and a requirement to go low gain, especially in the flare. All these configurations exhibited floating tendencies. As before the approach ratings were generally better than those for the flare and touchdown, and the basic configurations were marginally better than the A configurations (with integrator pole at $s+6$). There was no discernible trend with CG location for these configurations.

6.4 General Discussions

There was no clear preference for rate or angle command systems in the approach. Flight path control of the rate command systems may have been lower workload however the lack of longitudinal stability associated with these configurations resulted in poorer airspeed control, as found in reference 14. Once trimmed out the angle command configurations held either flight path or attitude and were generally well liked, except for the forces and sometimes intrusive trimming requirements to change the flight path. The exception to these observations is the angle of attack command system.

The angle of attack command configuration did not require much trimming with flight path changes and did not suffer airspeed control problems. It was rated well by all the pilots. Except for the airspeed characteristics, angle of attack command resembles the rate command systems in that for constant speed there is no appreciable trimming requirements with flight path changes. Considering the reduced order constant speed model of only angle of attack and pitch rate these two states give similar responses to a step input, therefore the rate like characteristics in the angle of attack response are not unexpected. The advantage, however, with the angle of attack command system is that as the speed changes there is a residual force that must either be held or trimmed out. The result of this in the flare is that as the aircraft is flared and the speed decays the pilot must hold a back force on the stick, and so monotonic stick forces are assured.

The angle of attack rate command system was not especially liked by any of the evaluation pilots. Its response was very sensitive, and by considering the angle of attack command system to be similar to a rate command system would therefore suggest the angle of attack rate command system may exhibit characteristics associated with an acceleration response. It is therefore not surprising the pilots did not nominate this as their favourite configuration. Unless the aerodynamics of subsonic transport aircraft changes dramatically in the future it is hard to argue for the further development of the angle of attack rate command system as a likely candidate for implementation in this class of aircraft.

There was a slight preference for the flight path command systems, both angle and rate, measured at the pilot station over those measured at the CG. This would be expected to be more apparent with an in-flight simulator, which can reproduce the normal acceleration cues at the pilot station associated with pitch acceleration, and for a larger aircraft where the pilot moment arm is greater and so would amplify this cue. Weingarten and Chalk, reference 1, found that as the pilot was moved further forward of the CG the pilot ratings improved due to the increased normal acceleration cue associated with the pitching. Due to the relationship between normal acceleration and flight path, equations 4 and 8, since the pilot senses normal acceleration at the pilot station it is realistic that he is better able to control normal acceleration and therefore flight path at the pilot station than at the centre of gravity. It is not possible to determine whether these results show a definite trend or are simply within the bounds of experimental error.

In the flare and touchdown the rate command systems all exhibited a tendency to float and generally received a median rating one point worse than their associated angle command system. Considering the limitations of this investigation this would appear to be fairly conclusive evidence, especially considering rate command systems are generally rated better in ground simulators than in flight. It is not unreasonable to expect that in flight the difference in ratings between the angle and rate command systems would be greater.

It is of course impossible to fully simulate the flare and touchdown in a ground simulator and any results obtained for this phase of the evaluation must be taken with caution. Although it is fare to conclude that the rate command systems do give poorer performance than angle command systems in the flare it is not possible to adequately separate the angle command systems to identify which was preferred or to further develop control laws for this phase in a ground simulator. These conclusions concur with the results of many previous investigations including that of reference 6. The exception to this was the preference expressed by the pilots towards the conventional response of the angle of attack command configurations.

The purpose of the hybrid configurations was to investigate whether long term response is important to a pilot. Configurations P-8-14 and P-8-16 were angle of attack command in the short term and rate command in the long term. Configuration P-8-14 was rated better, however the pilots did express some reservations about it, and their comments suggested a floating tendency. Configuration P-8-16 was rated poorer and exhibited a definite tendency to float, as well as airspeed problems and unpredictability. Both of these configurations exhibited rate command characteristics which were identified by the pilots and disliked.

Configuration P-8-41 was short term pitch rate and long term angle of attack command. This configuration was found to be more conventional than the previous two with no airspeed problems and a pleasant moderate force required in the flare. Configuration P-8-61 suffered from implementation problems and is therefore not included in these discussions.

It would therefore appear from both the pure and hybrid systems that configurations with long term angle command characteristics are preferred to those with long term rate command characteristics. This suggests that the long term response is critical to the pilot's perception of the handling qualities of aircraft, as concluded in reference 3.

The set I configurations were rated poorer than their equivalent set P configurations, however generally only by one or two rating points. The main reason for this was due to the over sensitive oscillatory response of these configurations, a feature of the unaugmented aircraft's low frequency and lightly damped short period mode which was retained in these configurations. Their equivalent set P configurations were dominated in the short term by a first order response due to the pole at (s+1.3), and so these responses were not so oscillatory, although still sensitive. As for the set P configurations better choice of short period dynamics for these configurations would have likely improved their ratings.

Overall the basic configurations with integrator pole at (s+1.3) were rated slightly better than those with the pole at (s+6). However due to the inherent poor dynamics of all the configurations it is not possible to discern any differences between the two designs.

The effects of the CG variations on the set P configurations were slight if any, however no real effect was expected for these configurations. If any effect was observed it was that for the pitch attitude command system a forward CG, therefore statically more stable aircraft, required higher forces to change the attitude, as would be expected, and for the pitch rate command system the aft CG was more sensitive, again as would be expected. Instead the extra evaluations serve to reinforce the results of the same configurations for the mid CG case. It is not possible to determine any effect of CG variation on the set I configurations. This is primarily due to the over sensitive response of these configurations.

Many of the results from this investigation have been affected by the choice of short period dynamics used throughout. However the results would tend to agree with the findings of Rossitto et al., reference 13, that the present lower level 1 CAP boundary could be raised slightly. It would also appear that the lower short period damping boundary is a little too generous.

The angle of attack command configurations of this investigation were preferred by the pilots to all others. Although direct flight path control and hold in the approach may not have been as good as for some others it posed no problems. To hold the acquired glideslope required little if any trimming and monotonic stick forces were felt in the flare. Considering the trimming requirements of an angle of attack command system, as the speed changes the lift will alter, therefore to maintain a constant flight path the angle of attack must be changed, or a force applied to the stick. This constant force must either be manually held or trimmed out, hence the requirement to trim with speed, or angle of attack changes. Considering now flight path changes, as the aircraft alters its flight path the lift required to maintain this new flight path will be different from before and so, for constant speed, a new angle of attack will need to be maintained. However for small flight path changes, such as level flight to glideslope, the change in lift required is minimal. Therefore if speed is maintained there will be minimal change in angle of attack and so minimal requirement to trim with small flight path changes.

Pitch attitude and flight path command systems do require unnatural trim changes with constant speed flight path changes. With speed changes a flight path command system will maintain flight path by automatically pitching to a new angle of attack, while a pitch attitude command system will maintain attitude at the expense of flight path, therefore requiring the pilot to select and trim to a new pitch attitude to maintain flight path for the new speed.

Rate command systems will hold their commanded parameter as for the angle command systems as long as no inputs are made by the pilot. The difference with these systems is that there is no requirement to trim to hold the new attitude or flight path. The drawback of this neutral static stability is that airspeed control becomes difficult due to no tactile feedback to the pilot, as found in reference 14. These systems would therefore normally be operated with the autothrottle engaged, and so speed control would not be a problem. However for manual thrust controlled flight any flight control system implementing a rate command type response will have a requirement for airspeed envelope protection, as in the A320/330/340.

The Airbus A320 uses a pitch attitude based command system in the flare. In their 7J7 simulation programmes Boeing considered both pitch attitude and flight path command systems for the flare. Both of these systems were also considered in this investigation, but neither of these systems produced as good ratings as the conventional angle of attack system. Boeing concluded that further development of flare control laws was required. Even with the latest fly-by-wire commercial transports it seems that a definitive flare control law has still to be achieved.

7 CONCLUSIONS

Twenty nine longitudinal control law configurations were designed, implemented and evaluated on a fixed base engineering ground simulator. These configurations covered a variety of concepts based on command of angle of attack, pitch attitude, flight path and their rates.

The slow and lightly damped short period dynamics of the basic unaugmented aircraft that were retained for the configurations had a detrimental effect on the results of the investigation.

The configurations incorporating proportional plus integral controllers suffered from the poor short period dynamics of the basic unaugmented aircraft, as a result no conclusions can be drawn from these configurations.

No definite conclusions could be drawn from the results of variations in CG.

For the approach phase the rate command systems were generally liked due to the lower pilot workload required for flight path control, however suffered from poor airspeed control due to their neutral static stability.

The pitch attitude and flight path command systems exhibited an unnatural trimming requirement with changes in flight path, but when trimmed out held the flight path well. Further work to define desirable control sensitivities for these command types is required.

In the flare the rate command systems floated, a tendency that was disliked by the pilots. The monotonic stick forces in the flare of the angle of attack, pitch attitude and flight path command systems was preferred.

The importance of the long term response to the handling qualities of transport aircraft was confirmed.

The results of the investigation would tend to agree with the conclusions of Rossitto et al., reference 13, that the lower level one CAP boundary could be raised slightly. Additionally the lower level one short period damping requirements would seem a little relaxed.

The angle of attack command systems were rated best of all the configurations. The pilots preferred the conventional response of these configurations with the minimal trim requirements with flight path changes, positive forces with speed changes and monotonic stick forces in the flare.

REFERENCES

1 Weingarten, Norman C and Chalk, Charles R, "In-Flight Investigation of Large Airplane Flying Qualities for Approach and Landing", AFWAL TR-81-3118, December 1981

2 Berthe, Charles J; Chalk, Charles R and Sarrafian, Shahan K, "Pitch Rate Flight Control Systems in the Flared Landing Task and Design Criteria Development", NASA CR-172491, October 1984

3 Weingarten, Norman C; Berthe, Charles J; Rynaski, Edmund G and Sarrafian, Shahan, K, "Flared Landing Approach Flying Qualities", NASA CR-178188, December 1986

4 Anonymous, "Flying Qualities of Piloted Airplanes", MIL-F-8785C, November 1980

5 Airbus Industrie, "A320 Flight Crew Operating Manual, Volume 1 - Systems Description", Revision 06, May 1988.

6 Ranz, Dale and Berthe, Charles J, "Boeing 7J7 Fly-By-Wire Control Development", 31st Society of Experimental Test Pilots Symposium Proceedings, September 1987

7 Sankrithi, Mithra M K V and Bryant W F, "7J7 Manual Flight Control Functions", AIAA-87-2454-CP, presented at the AIAA Guidance, Navigation and Control Conference, Monterey, California, August 1987

8 Arent, Lauren and Falatko, Jay, "757 Fly-By-Wire Demonstrator Flight Test", AIAA-92-4099-CP, presented at the AIAA 6th Biannual Flight Test Conference, 1992

9 Tobie, Harold N; Elliot, Elden M and Malcom, Lawrence G, "A New Longitudinal Handling Qualities Criterion", presented at the National Aerospace Electronics Conference, Dayton, Ohio, May 1966

10 Melvin, Bill and Beatty, Tony, "Boeing 777 - Fly-By-Wire Demonstrations", Interpilot Magazine, Quarterly review of the International Federation of Air Line Pilots Associations, March 1993

11 Alder, Martin, "Flying the 757 FBW Aircraft", British Airways Flight Crew Information Service, 31 January 1993

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

13 Rossitto, Ken F; Hodgkinson, John; Williams, Todd M; Leggett, Dave B; Bailey, Randall E and Ohmit, Eric E, "Initial Results of an In-Flight Investigation of Longitudinal Flying Qualities for Augmented, Large Transports in the Approach and Landing", AIAA-93-3816-CP, presented at the AIAA Guidance, Navigation and Control Conference, Monterey, California, August 1993

14 van der Geest, P J; Nieuwpoort, A M H and Borger, J, "A Simulator Evaluation of Various Manual Control Concepts for Fly-By-Wire Transport Aircraft", AIAA-92-4328-CP, presented at the AIAA Navigation, Guidance and Control Conference, 1992

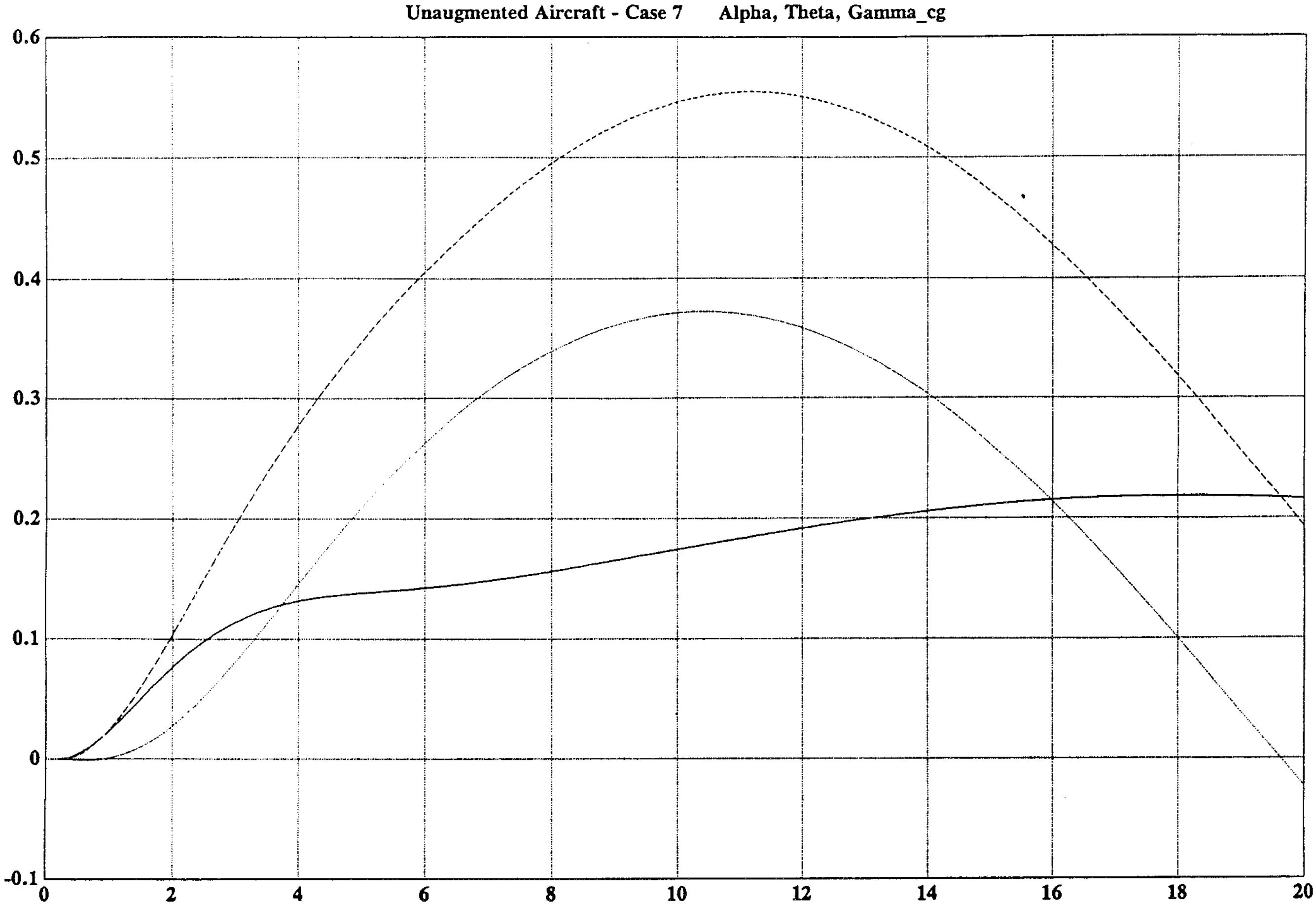
15 Rynaski, Edmund G, "Flying Qualities in the Time Domain", Calspan Report No. 7205-3, August 1984

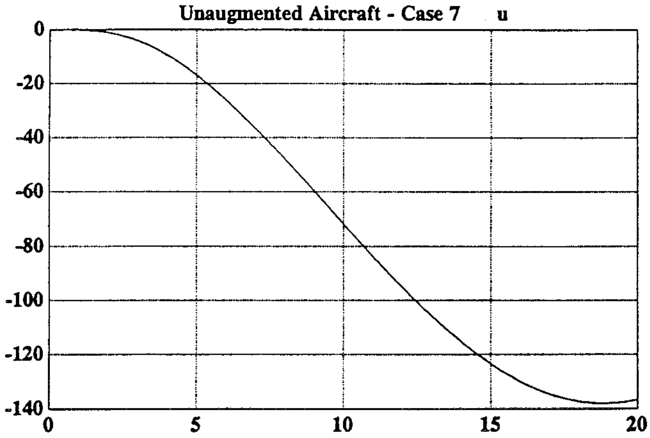
16 MATLAB, The MathWorks, Inc., Massachusetts, Version 4, 1993

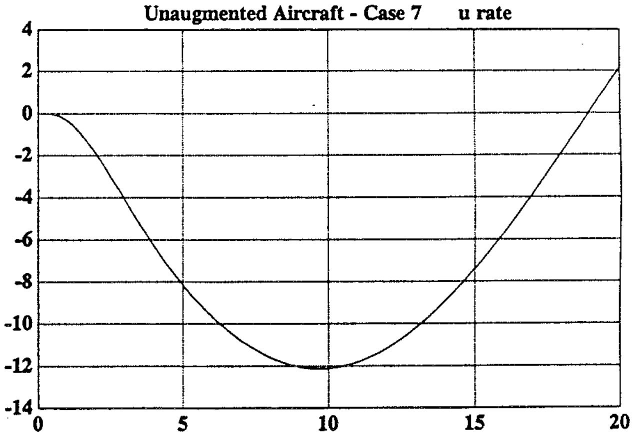
17 Neal, T Peter and Smith, Rogers E, "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes", AFFDL-TR-70-74, June 1970

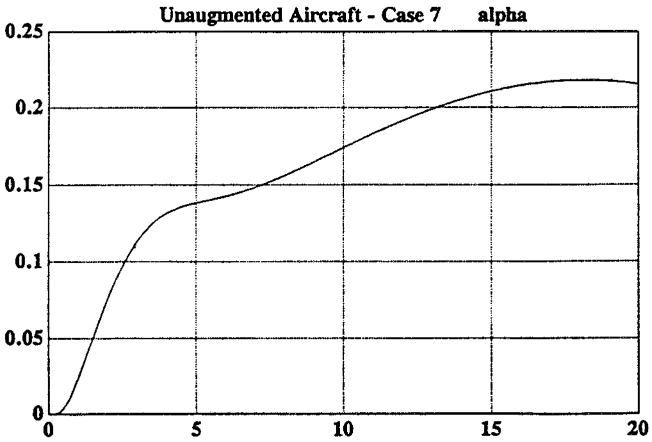
Appendix A

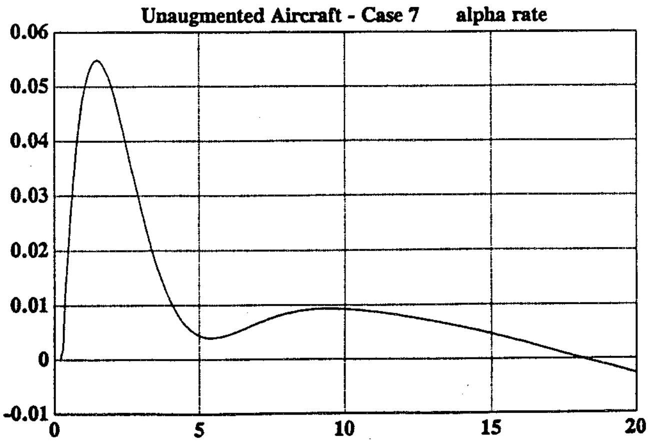
UNAUGMENTED AIRCRAFT TIME HISTORY RESPONSES

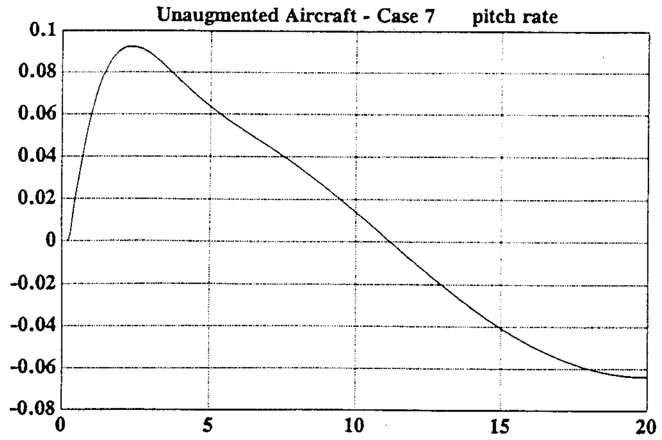

Unaugmented Aircraft - Case 7 Alpha, Theta, Gamma_cg

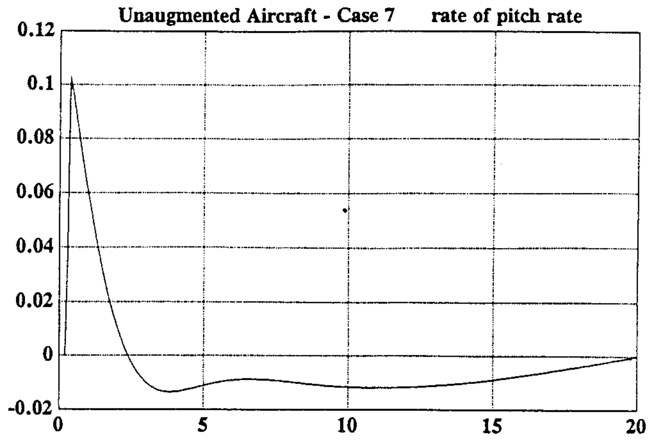

Unaugmented Aircraft - Case 7 u

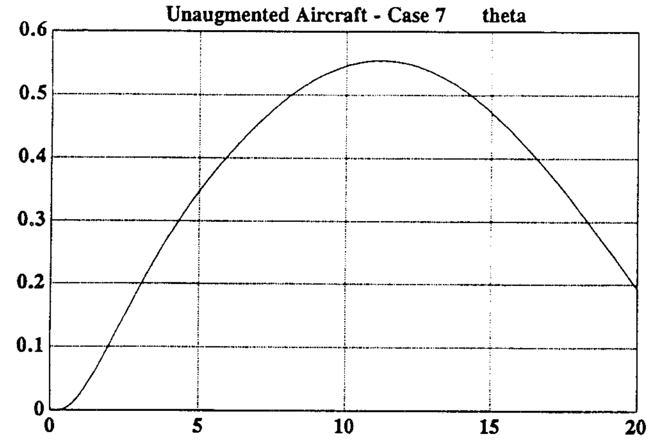

Unaugmented Aircraft - Case 7 u rate

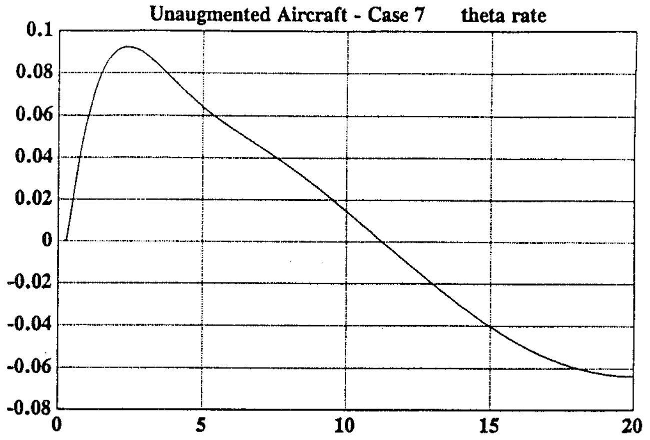

Unaugmented Aircraft - Case 7 alpha

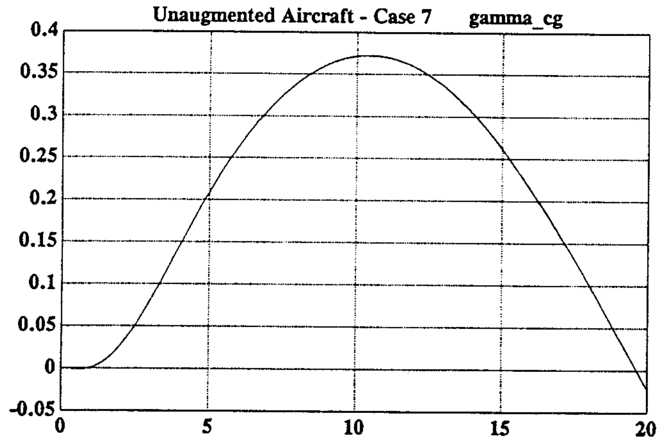

Unaugmented Aircraft - Case 7 alpha rate

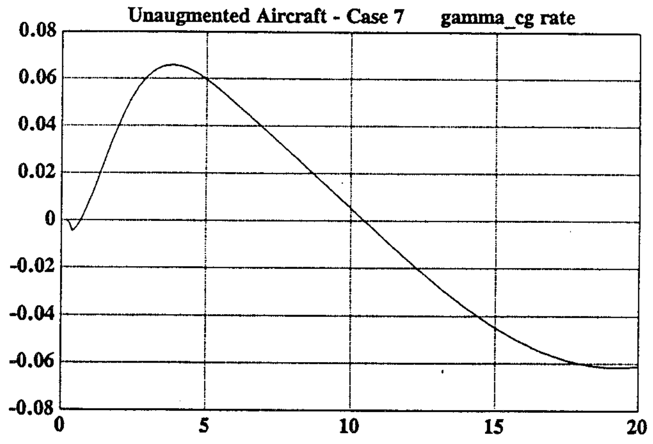

Unaugmented Aircraft - Case 7 pitch rate

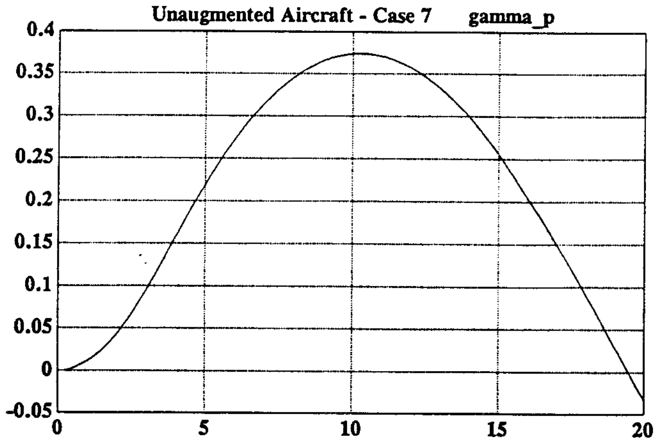

Unaugmented Aircraft - Case 7 rate of pitch rate

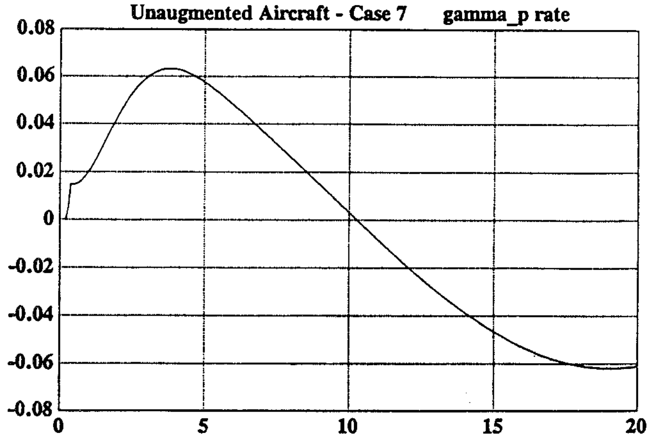

Unaugmented Aircraft - Case 7 theta


Unaugmented Aircraft - Case 7 theta rate

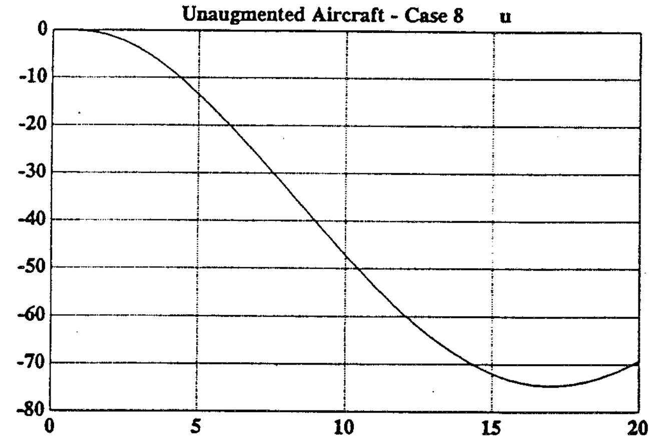

Unaugmented Aircraft - Case 7 gamma_cg

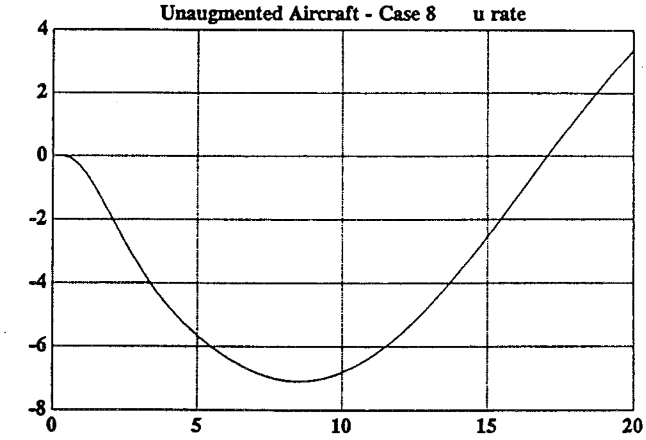

Unaugmented Aircraft - Case 7 gamma_cg rate

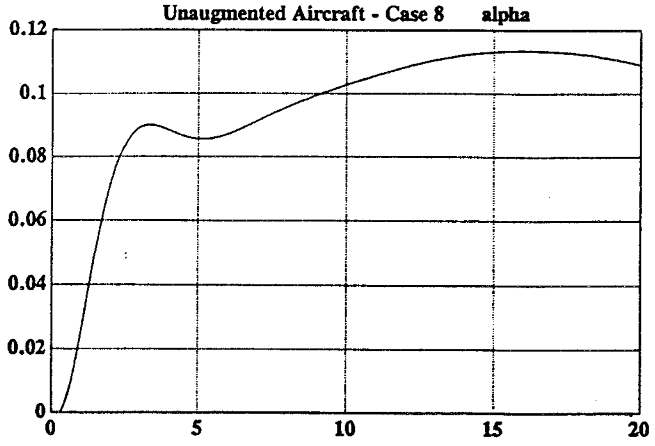

Unaugmented Aircraft - Case 7 gamma_p

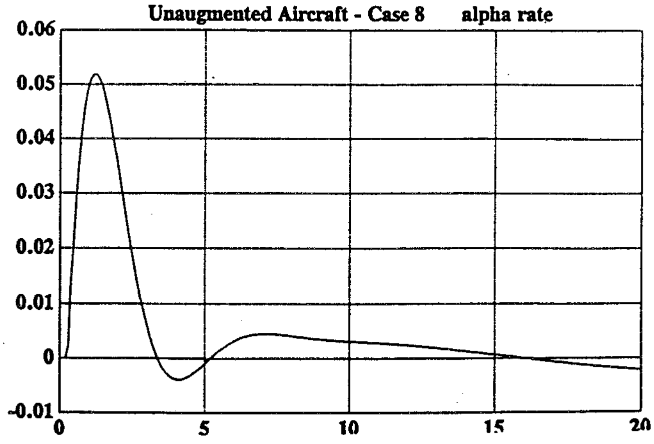

Unaugmented Aircraft - Case 7 gamma_p rate

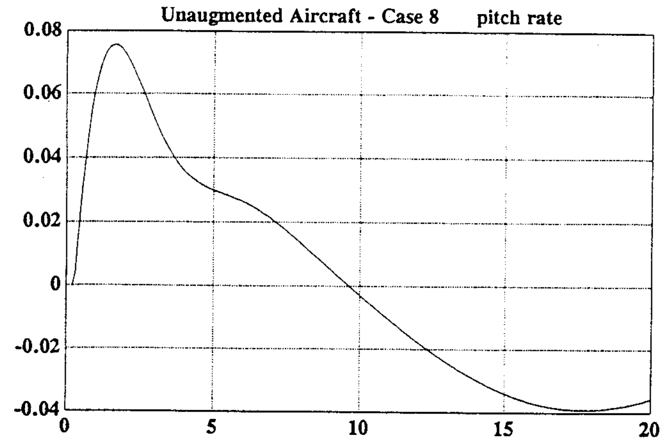

Unaugmented Aircraft - Case 8 Alpha, Theta, Gamma_cg
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
2
4
6
8
10
12
14
16
18
20

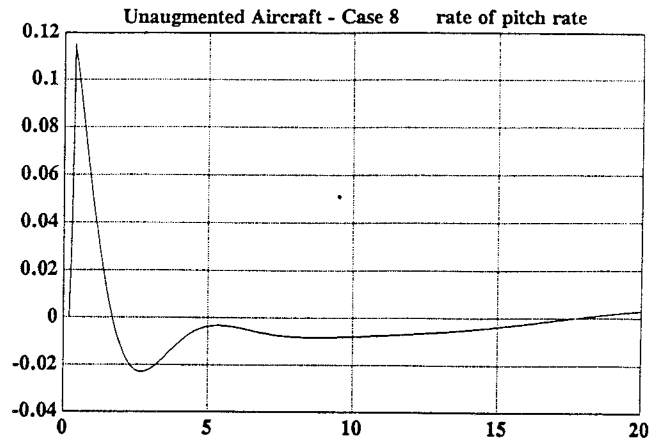

Unaugmented Aircraft - Case 8 u
0
-10
-20
-30
-40
-50
-60
-70
-80
0
5
10
15
20

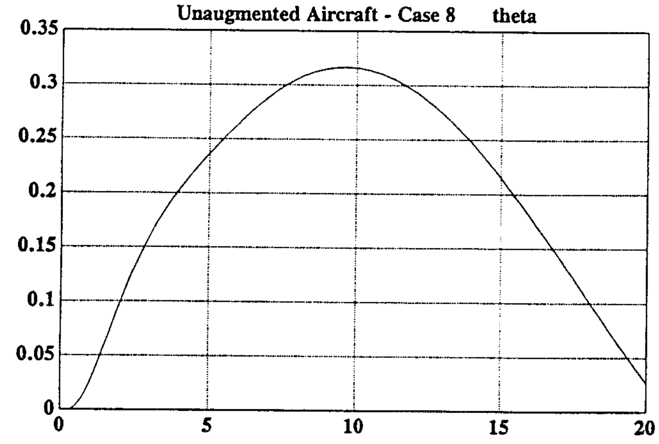

Unaugmented Aircraft - Case 8 u rate
4
2
0
-2
-4
-6
-8
0
5
10
15
20

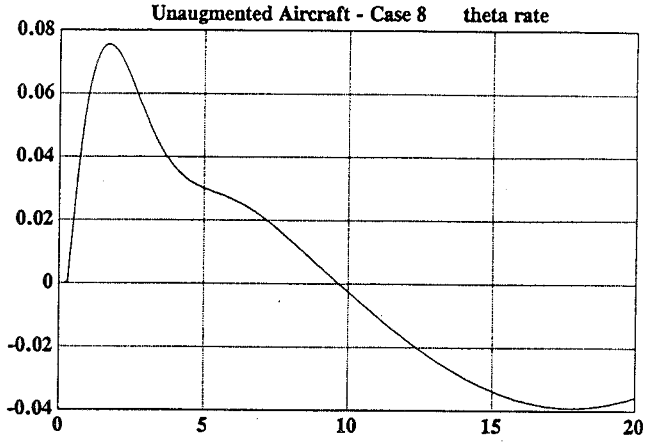

Unaugmented Aircraft - Case 8 alpha
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

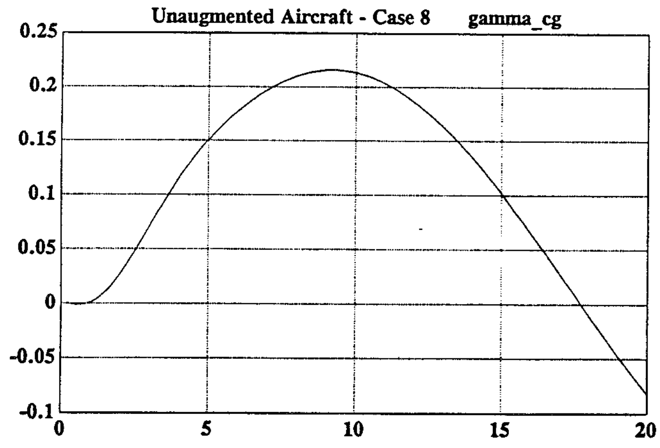

Unaugmented Aircraft - Case 8 alpha rate
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

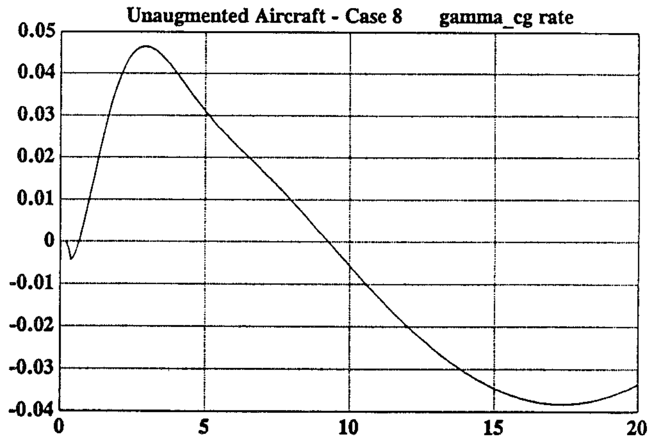

Unaugmented Aircraft - Case 8 pitch rate
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

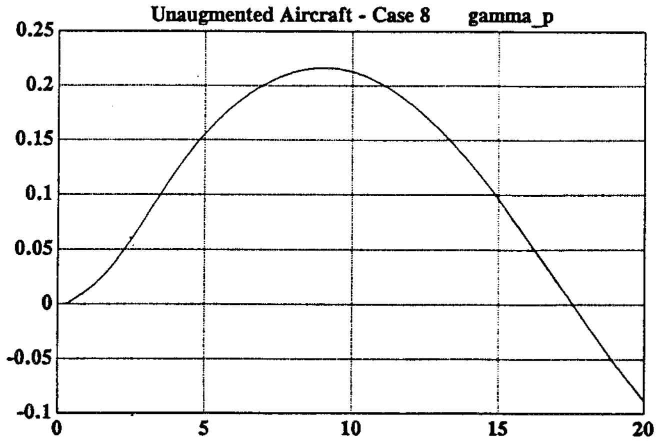

Unaugmented Aircraft - Case 8 rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

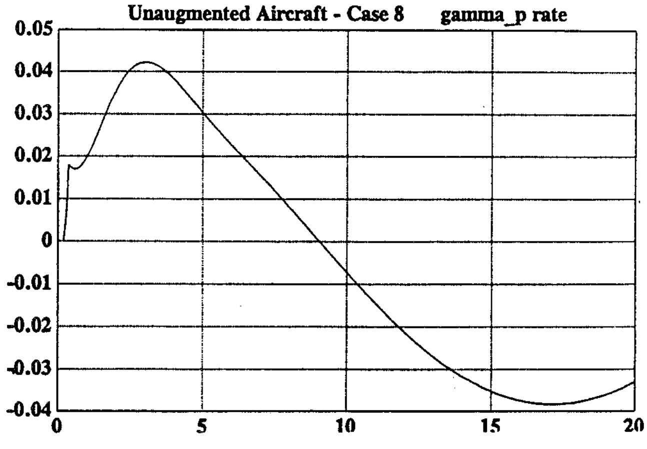

Unaugmented Aircraft - Case 8 theta
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20

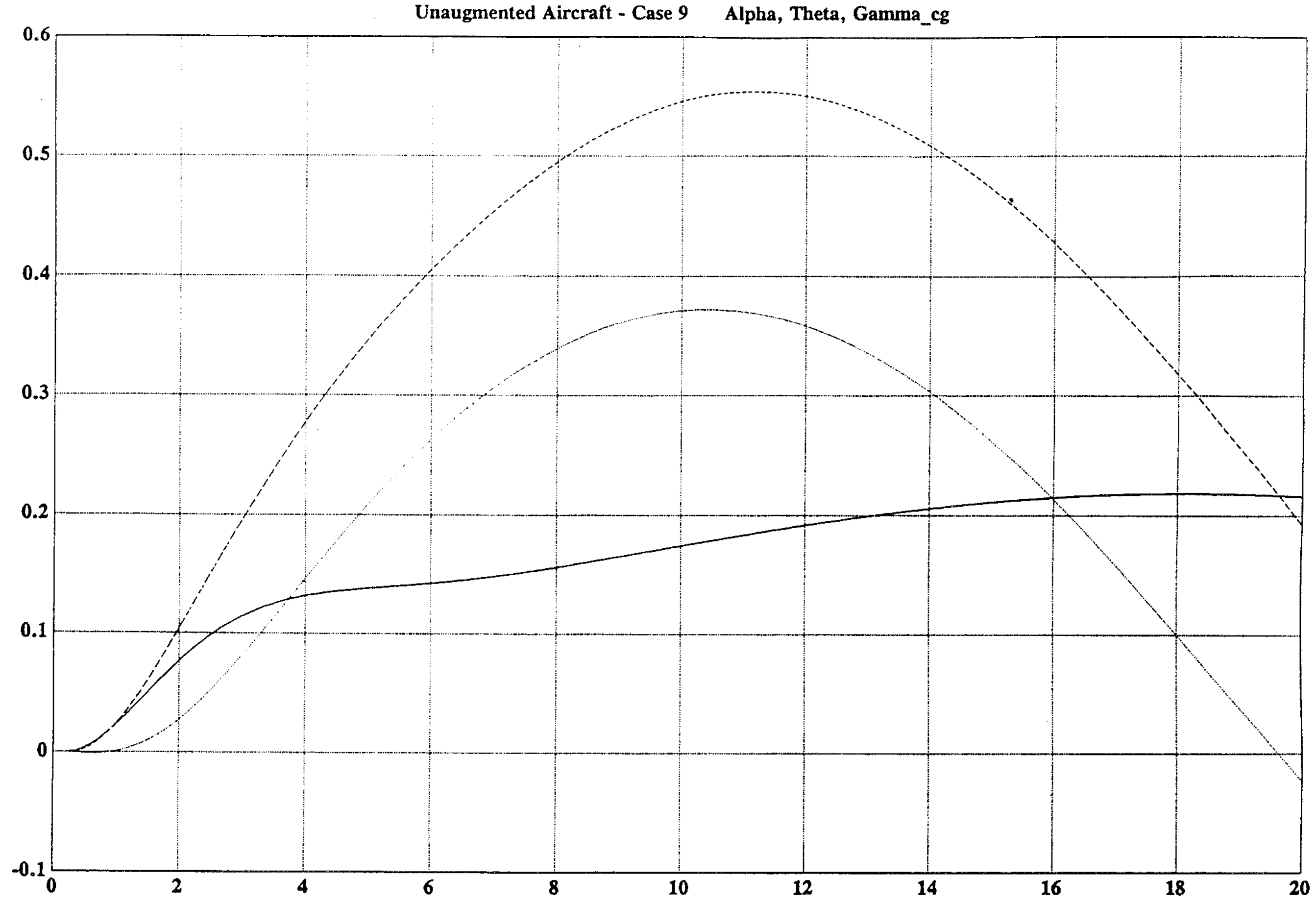

Unaugmented Aircraft - Case 8 theta rate
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

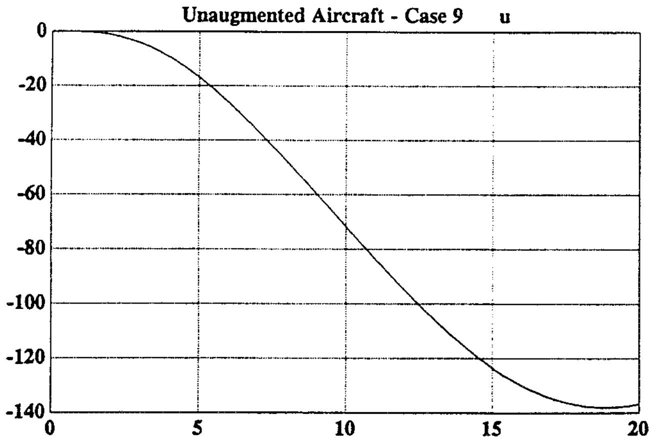

Unaugmented Aircraft - Case 8 gamma_cg
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20

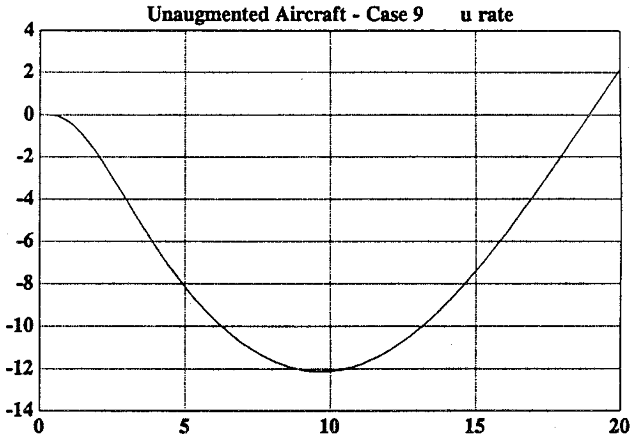

Unaugmented Aircraft - Case 8 gamma_cg rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
5
10
15
20

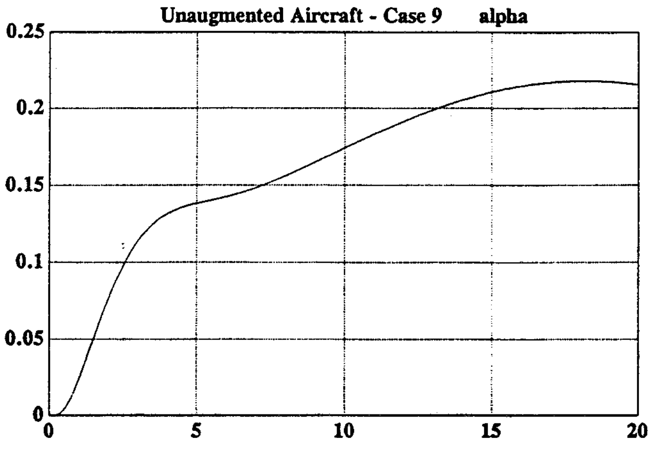

Unaugmented Aircraft - Case 8 gamma_p
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20

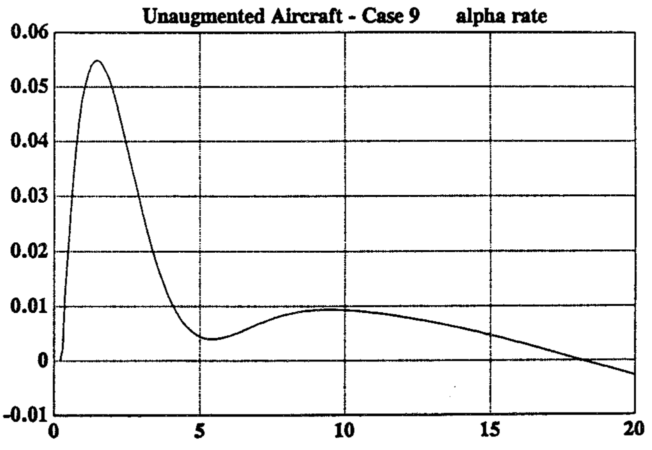

Unaugmented Aircraft - Case 8 gamma_p rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
5
10
15
20

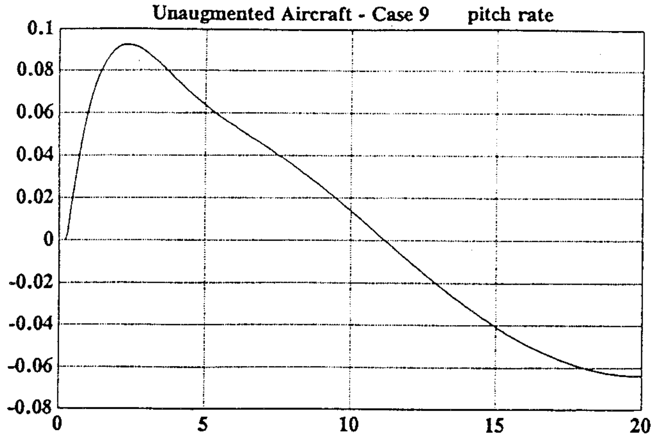

Unaugmented Aircraft - Case 9 Alpha, Theta, Gamma_cg

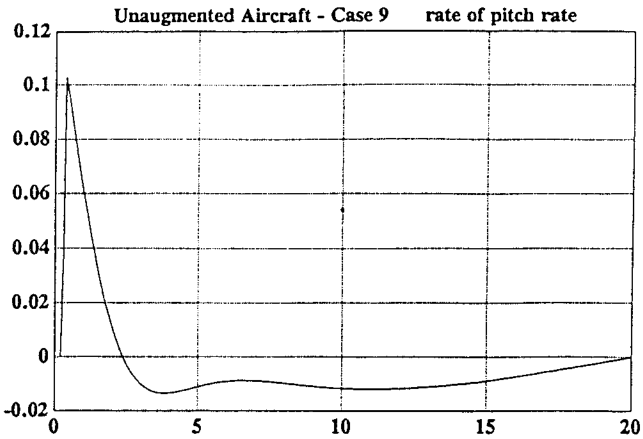

Unaugmented Aircraft - Case 9 u

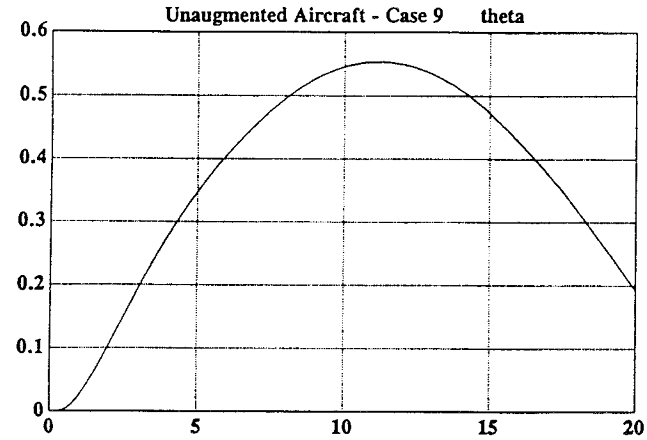

Unaugmented Aircraft - Case 9 u rate

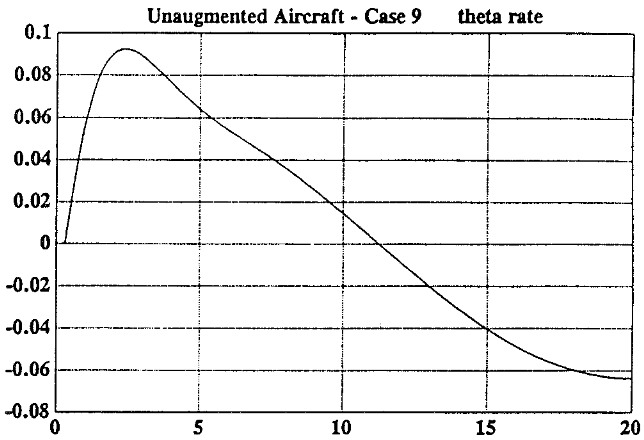

Unaugmented Aircraft - Case 9 alpha

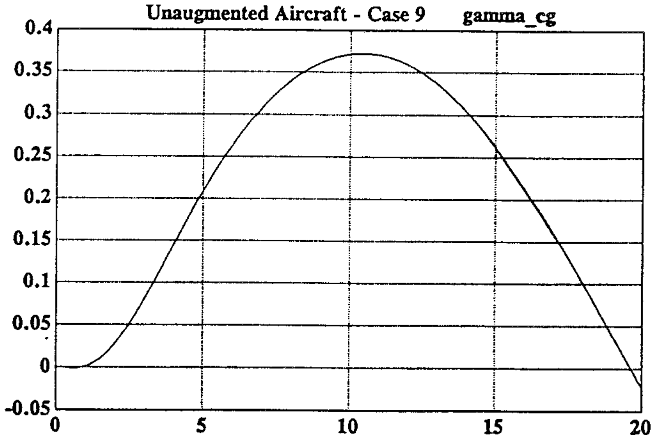

Unaugmented Aircraft - Case 9 alpha rate

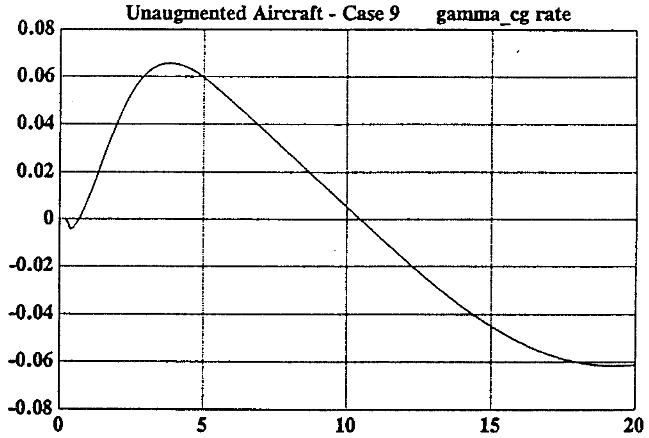

Unaugmented Aircraft - Case 9 pitch rate

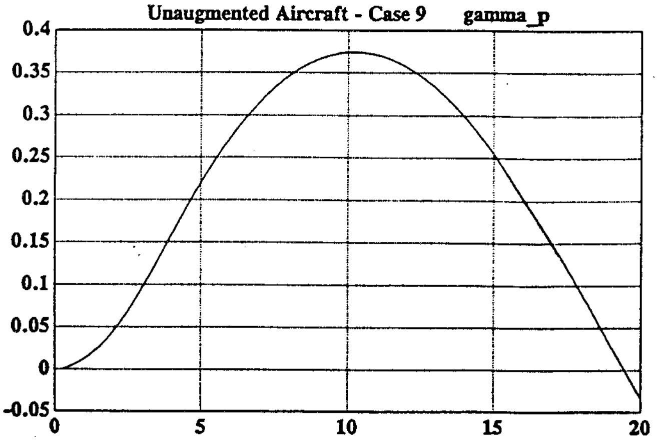

Unaugmented Aircraft - Case 9 rate of pitch rate

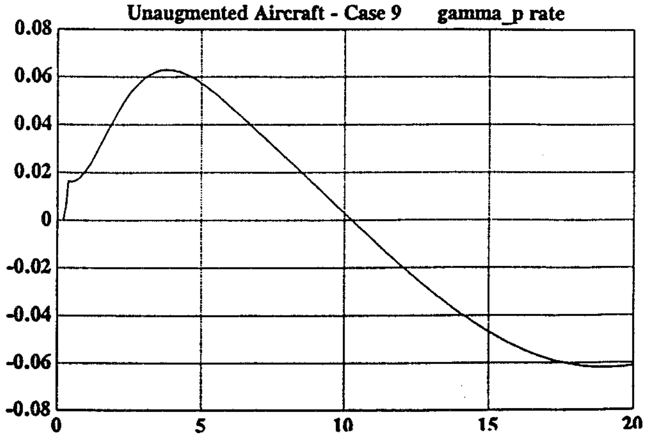

Unaugmented Aircraft - Case 9 theta


Unaugmented Aircraft - Case 9 theta rate


Unaugmented Aircraft - Case 9 gamma_cg

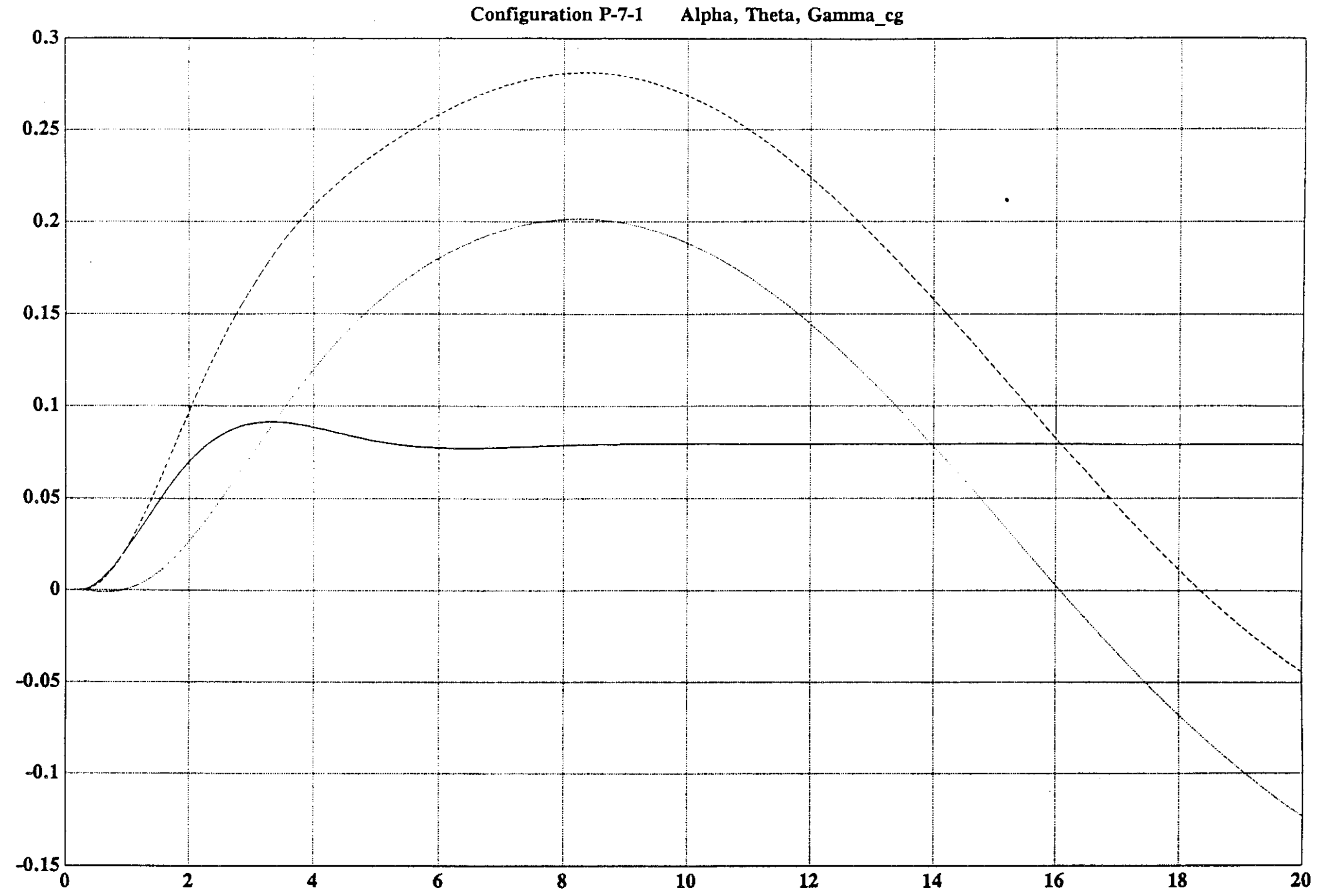

Unaugmented Aircraft - Case 9 gamma_cg rate

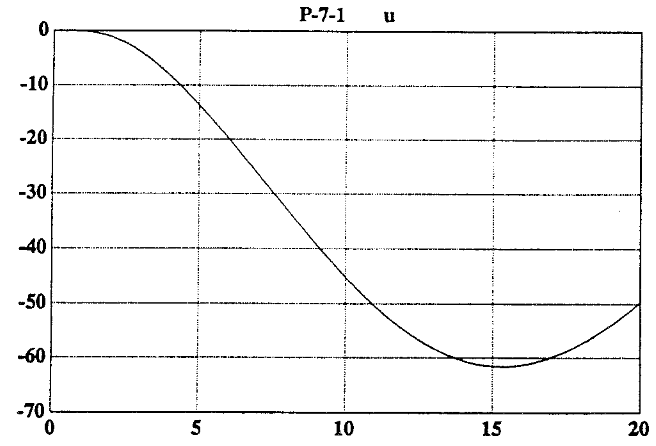

Unaugmented Aircraft - Case 9 gamma_p

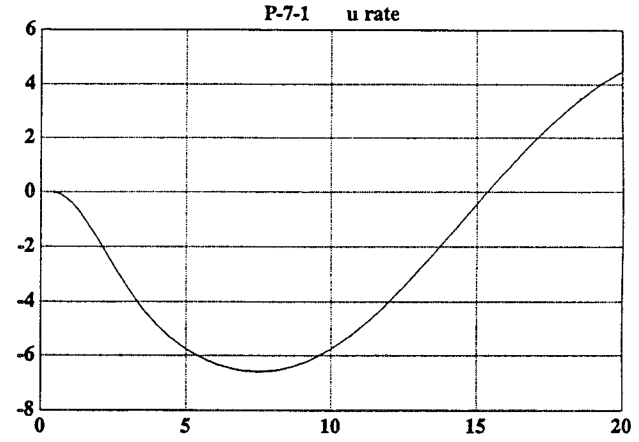

Unaugmented Aircraft - Case 9 gamma_p rate

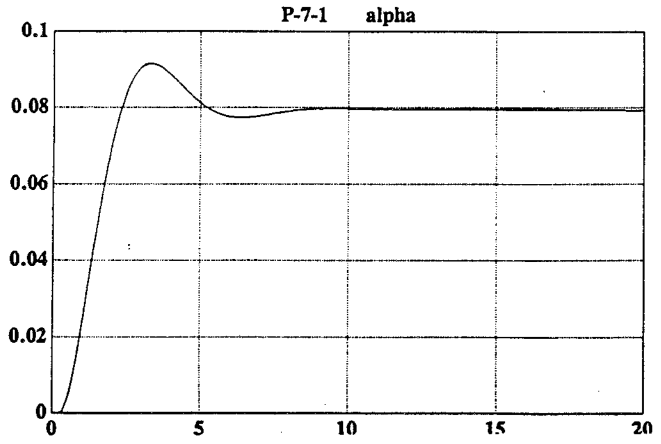
Appendix B

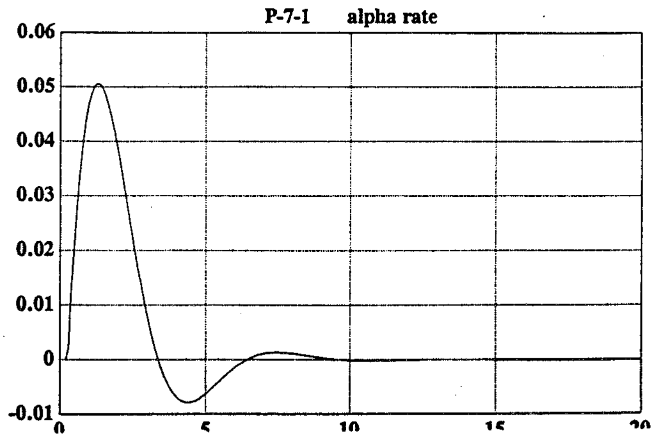
SET P CONFIGURATION TIME HISTORY RESPONSES

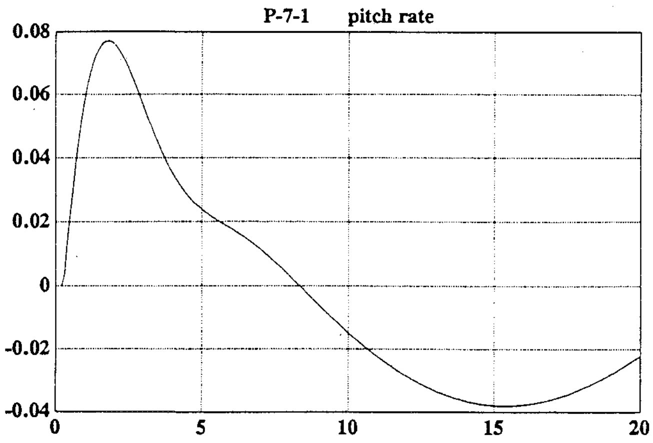

Configuration P-7-1 Alpha, Theta, Gamma_cg
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
2
4
6
8
10
12
14
16
18
20

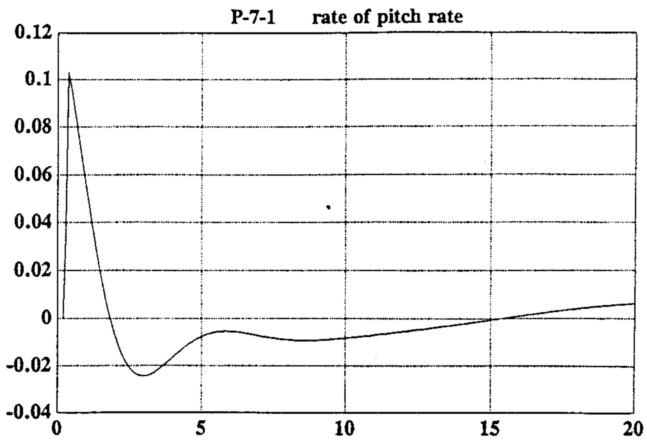

P-7-1 u
0
-10
-20
-30
-40
-50
-60
-70
0
5
10
15
20

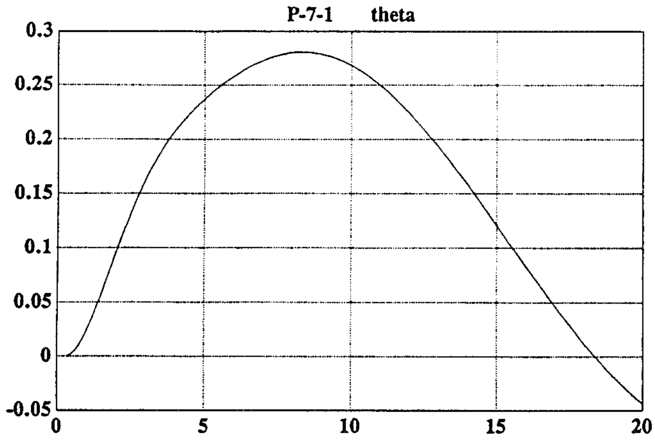

P-7-1 u rate
6
4
2
0
-2
-4
-6
-8
0
5
10
15
20

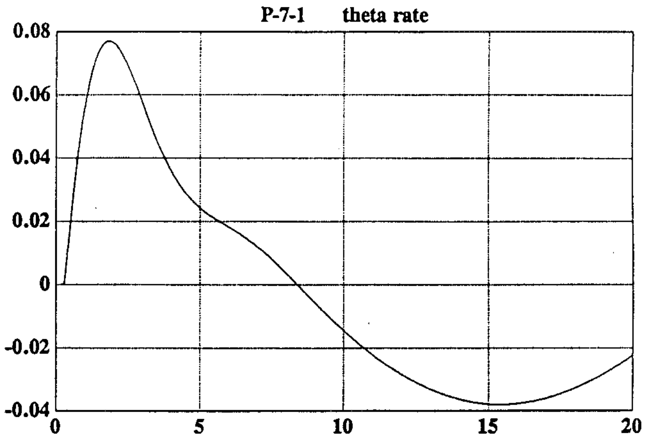

P-7-1 alpha
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

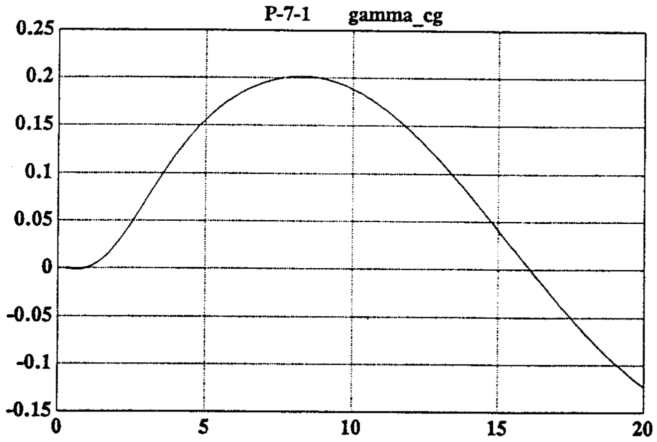

P-7-1 alpha rate
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

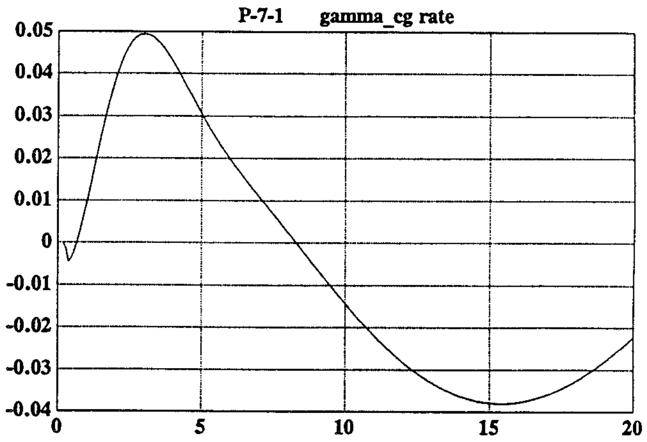

P-7-1 pitch rate
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

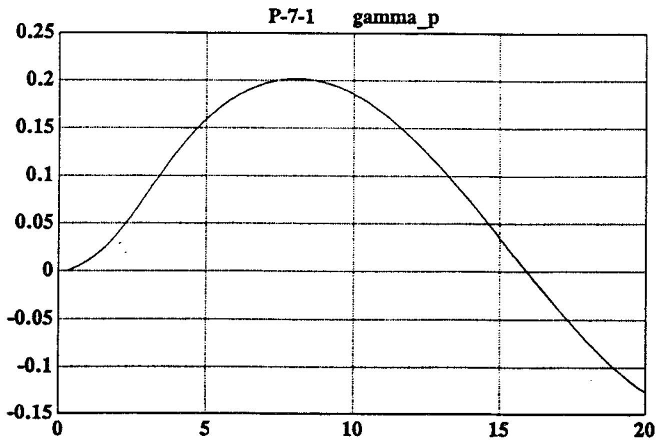

P-7-1 rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

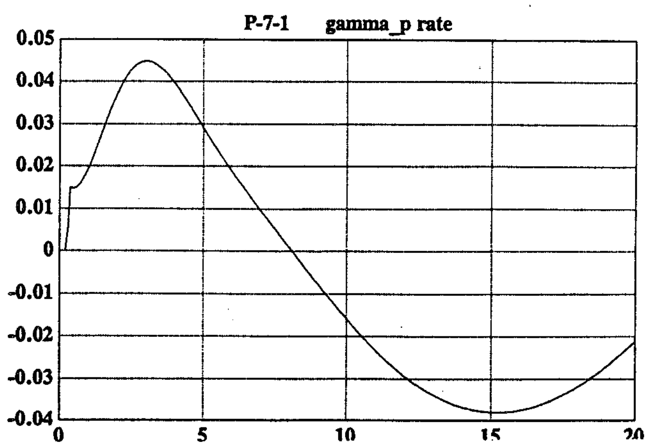

P-7-1 theta
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
15
20

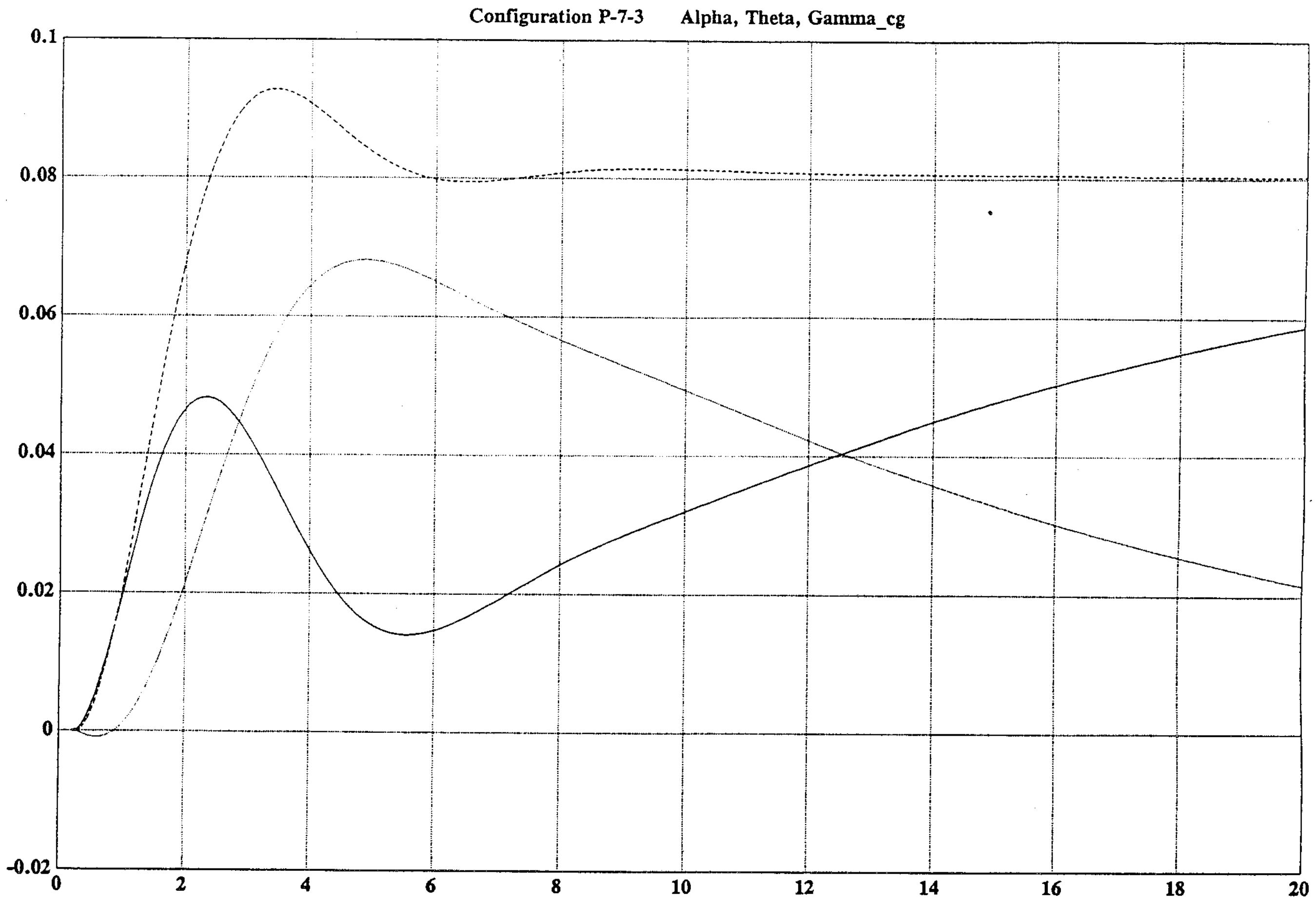

P-7-1 theta rate
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

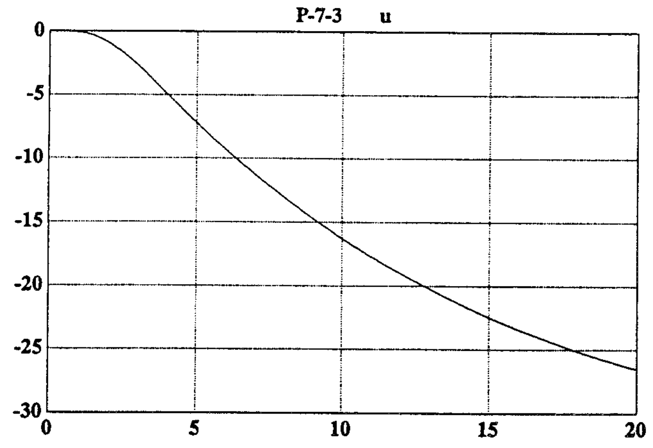

P-7-1 gamma_cg
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20

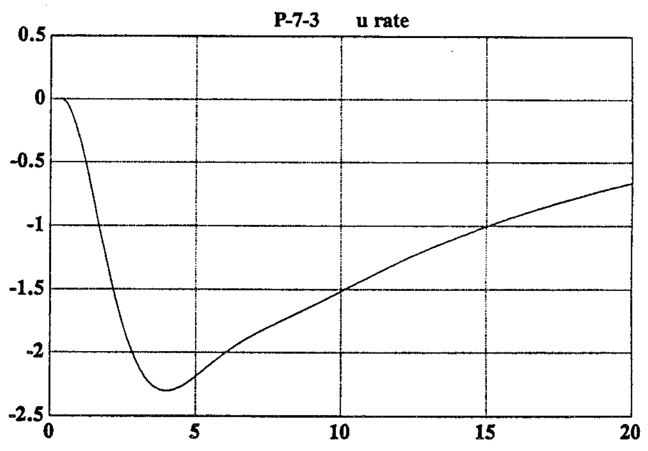

P-7-1 gamma_cg rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
5
10
15
20

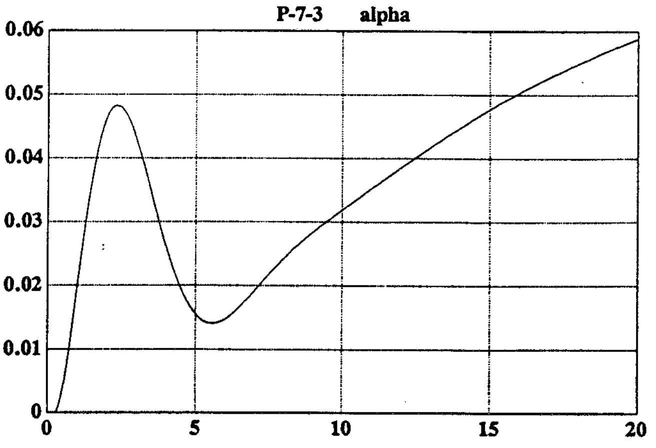

P-7-1 gamma_p
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20

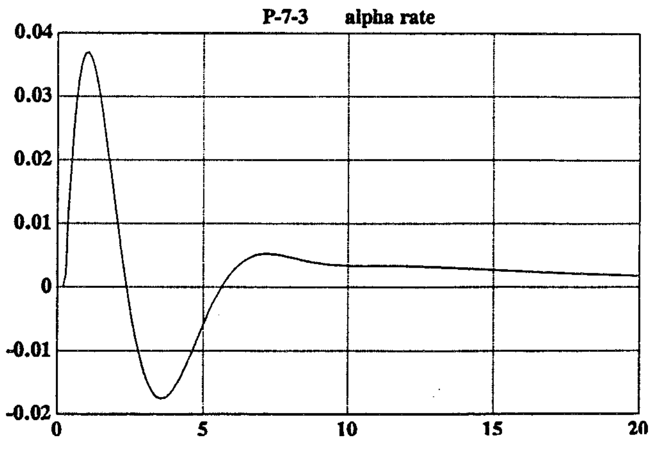

P-7-1 gamma_p rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
5
10

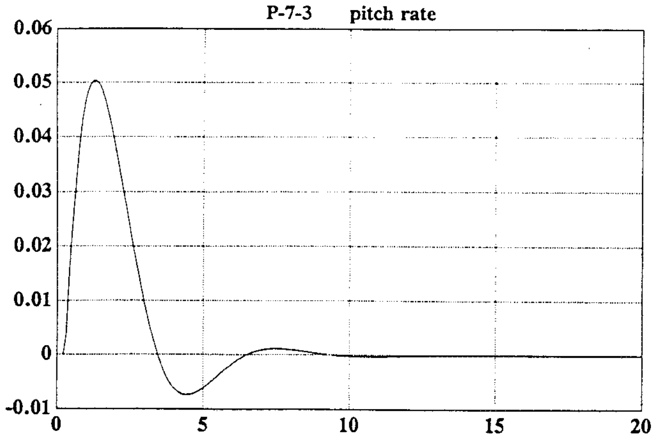

Configuration P-7-3 Alpha, Theta, Gamma_cg
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
2
4
6
8
10
12
14
16
18
20

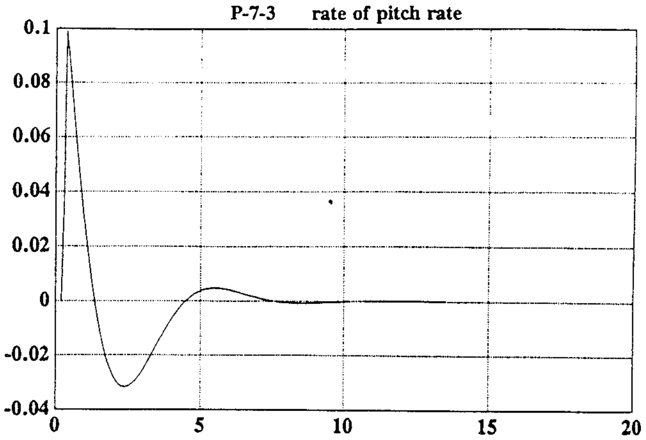

P-7-3 u
0
-5
-10
-15
-20
-25
-30
0
5
10
15
20

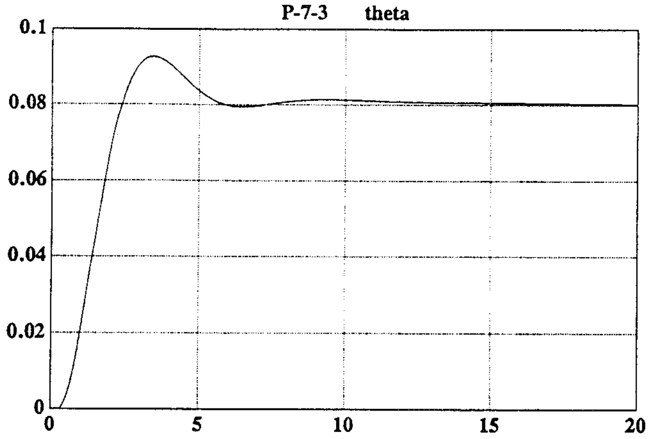

P-7-3 u rate
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20

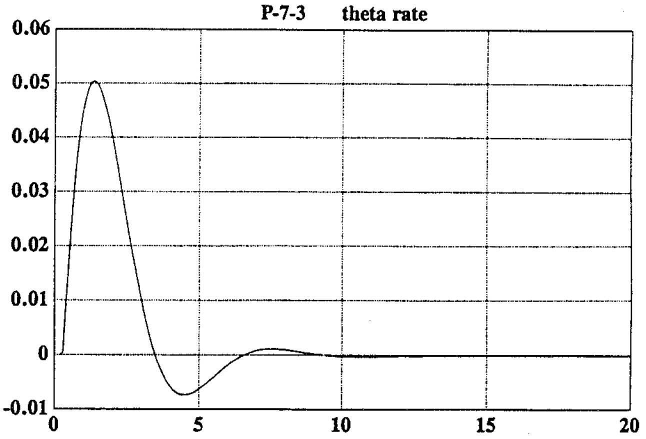

P-7-3 alpha
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

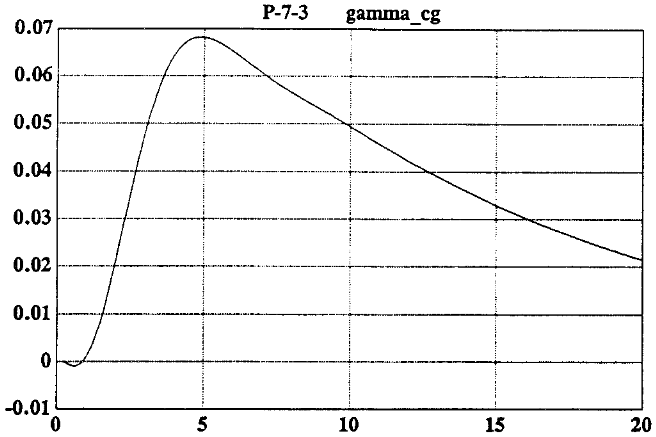

P-7-3 alpha rate
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20

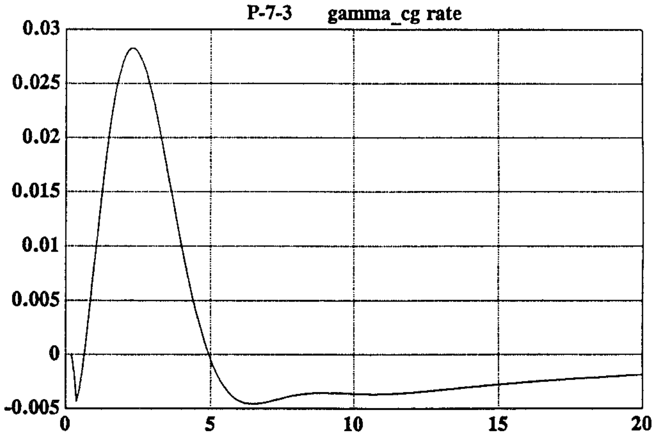

P-7-3 pitch rate

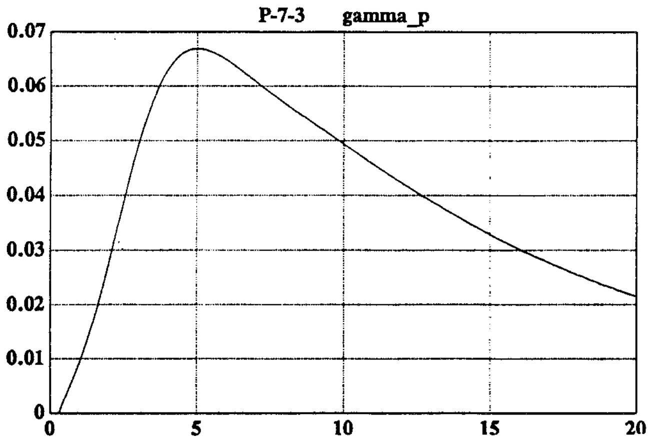

P-7-3 rate of pitch rate

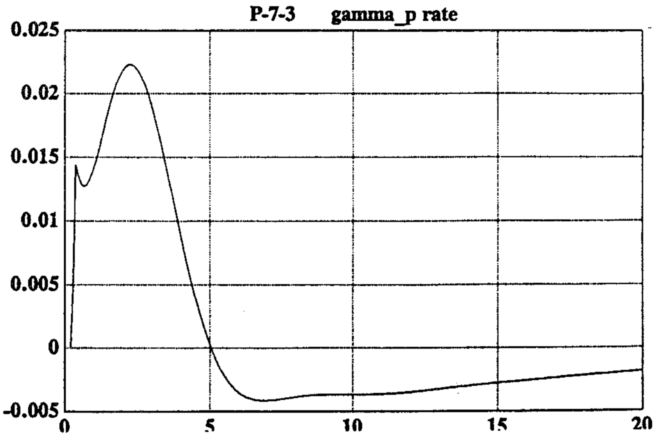

P-7-3 theta

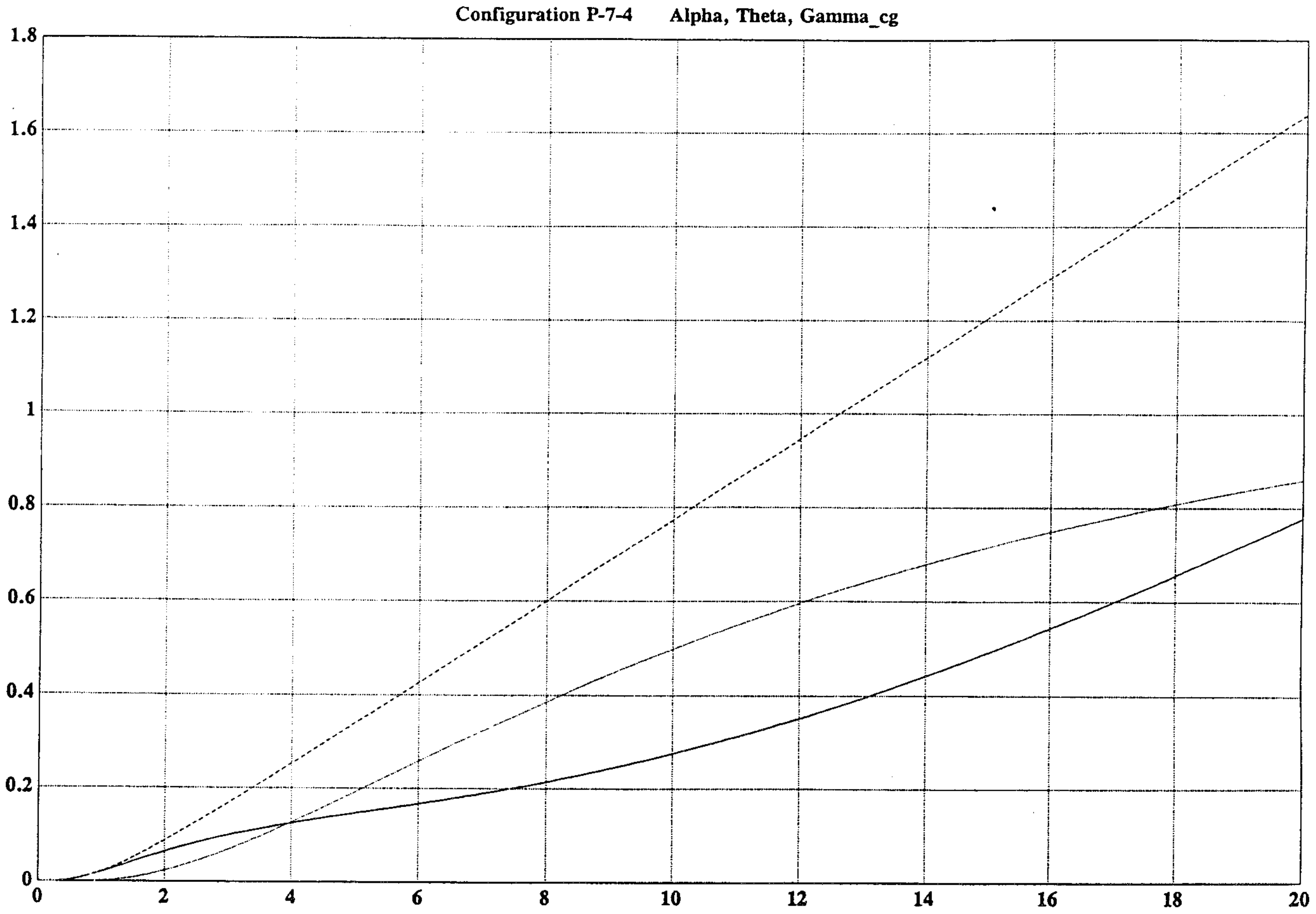

P-7-3 theta rate

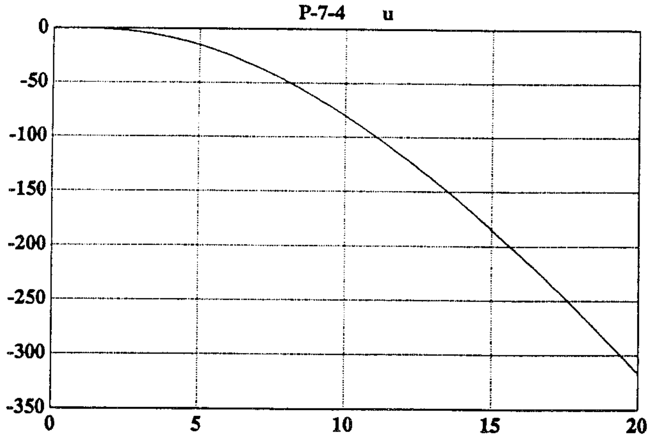

P-7-3 gamma_cg

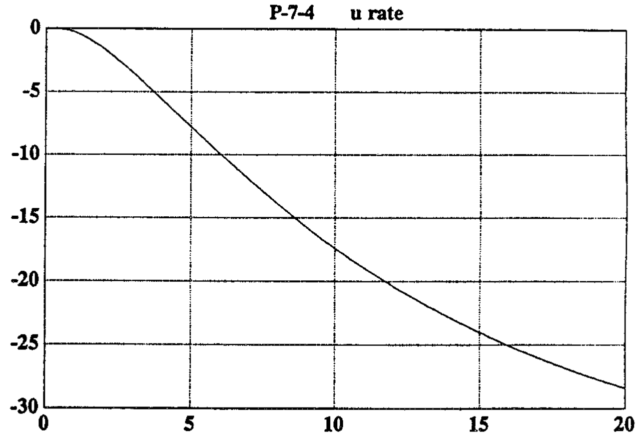

P-7-3 gamma_cg rate

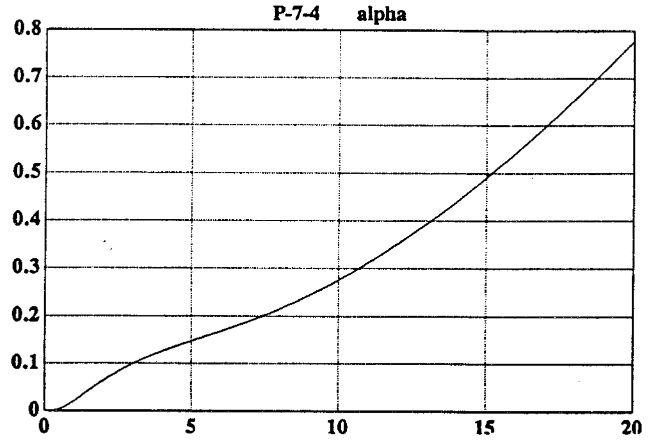

P-7-3 gamma_p

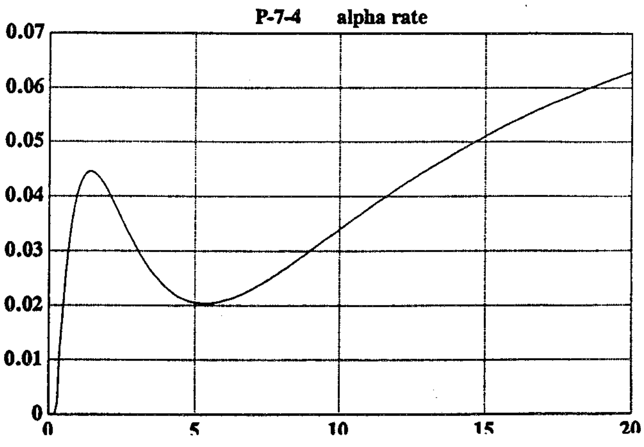

P-7-3 gamma_p rate

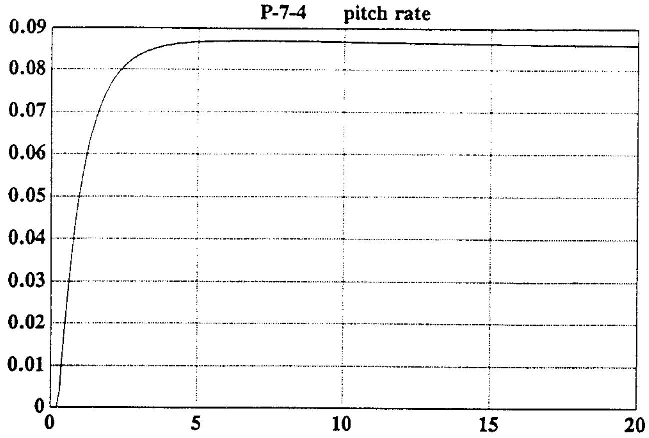

Configuration P-7-4 Alpha, Theta, Gamma_cg
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

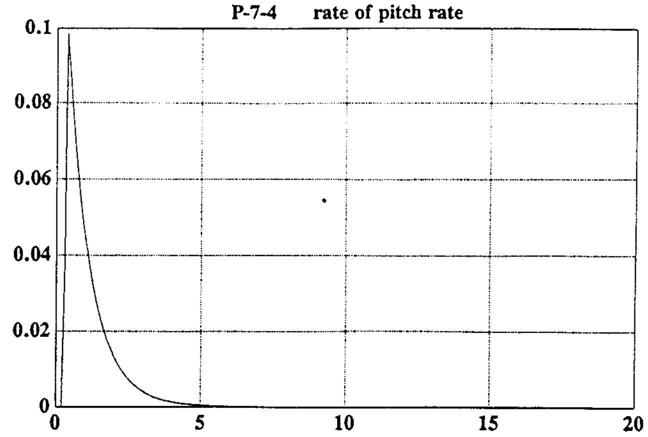

P-7-4 u
0
-50
-100
-150
-200
-250
-300
-350
0
5
10
15
20

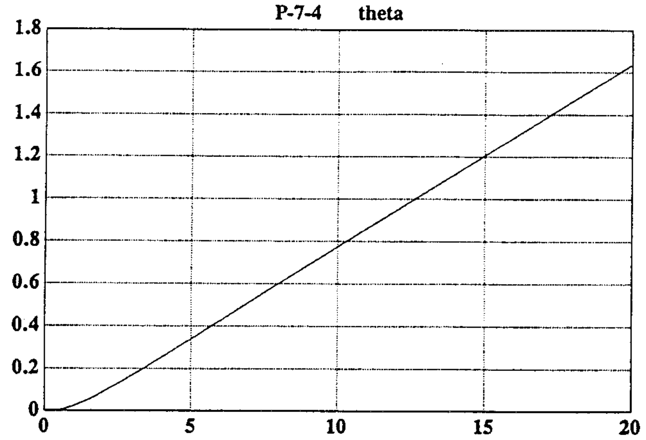

P-7-4 u rate
0
-5
-10
-15
-20
-25
-30
0
5
10
15
20

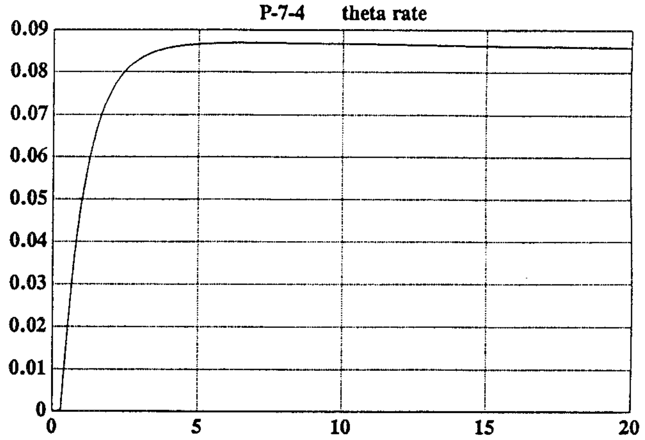

P-7-4 alpha
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

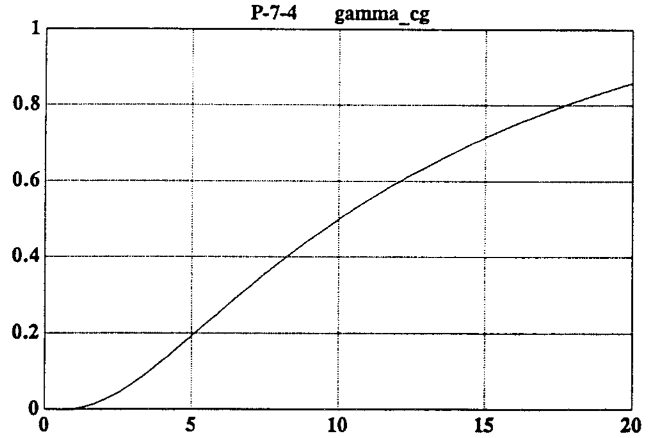

P-7-4 alpha rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

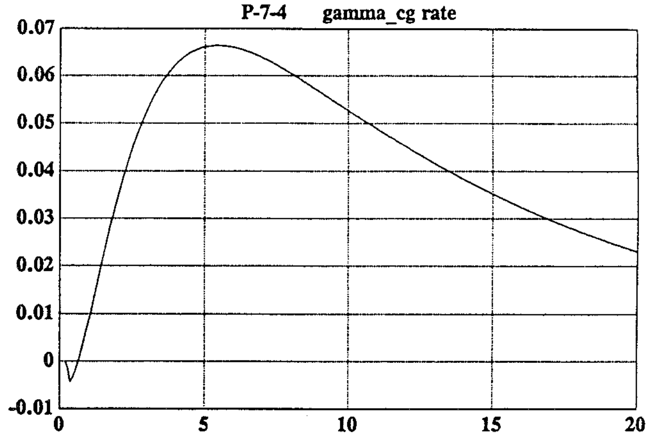

P-7-4 pitch rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

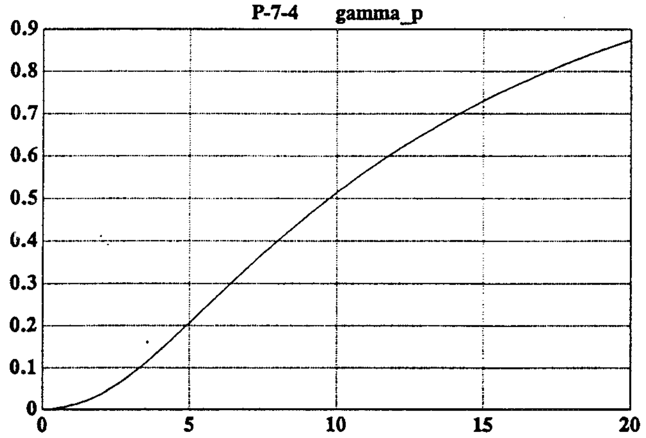

P-7-4 rate of pitch rate
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

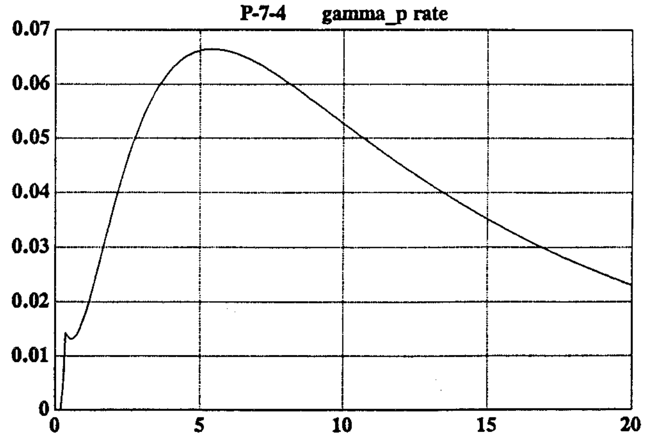

P-7-4 theta
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20

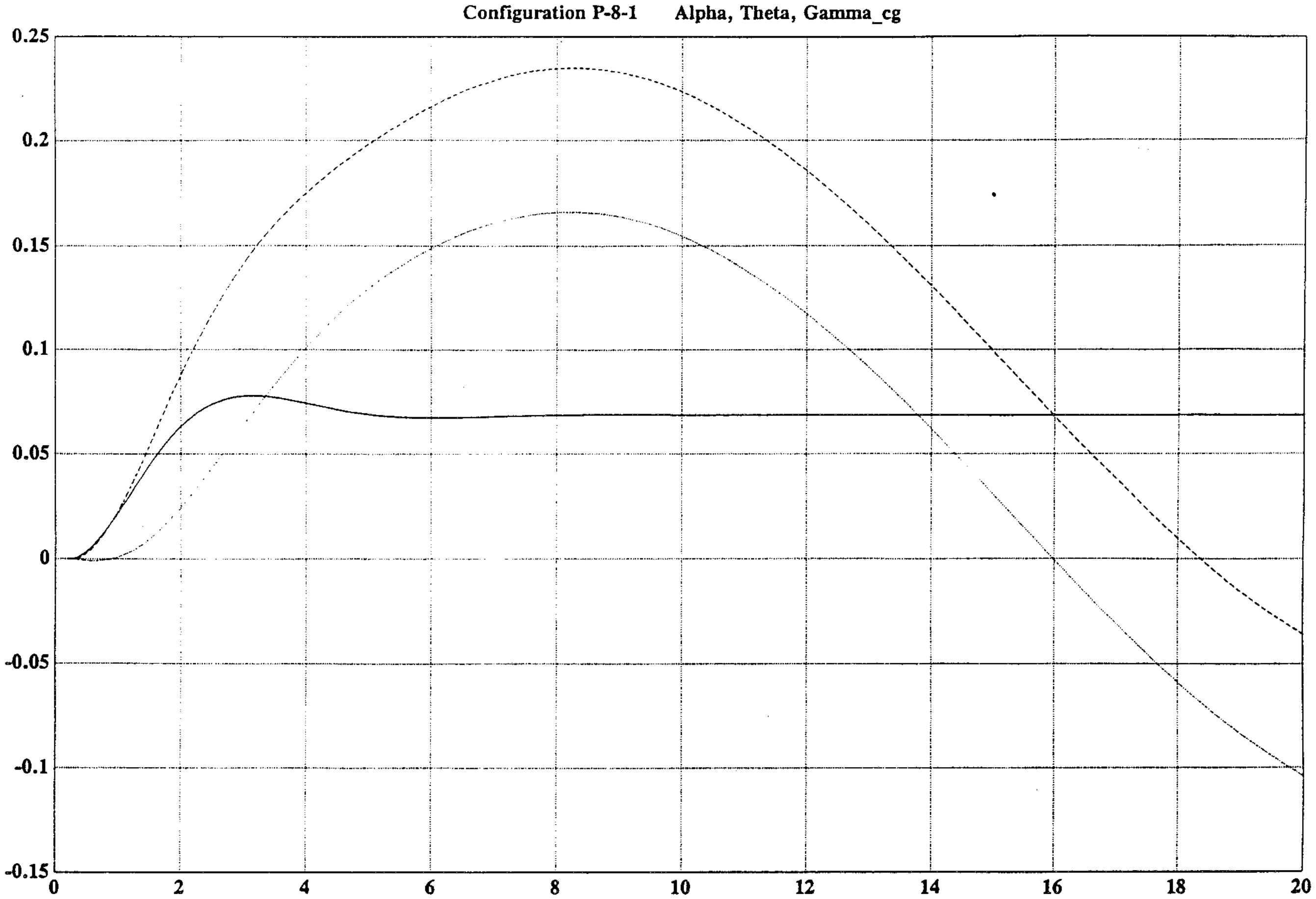

P-7-4 theta rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

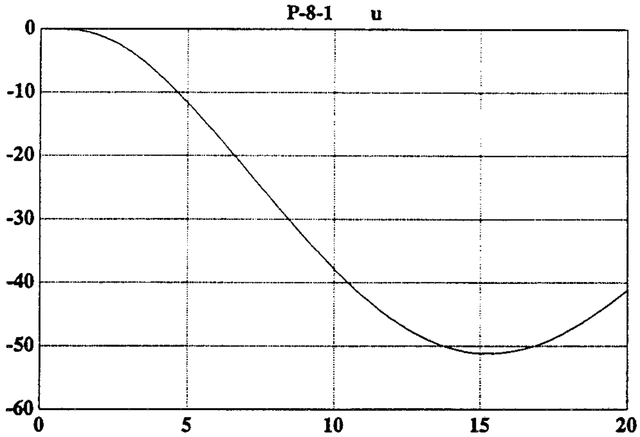

P-7-4 gamma_cg
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20

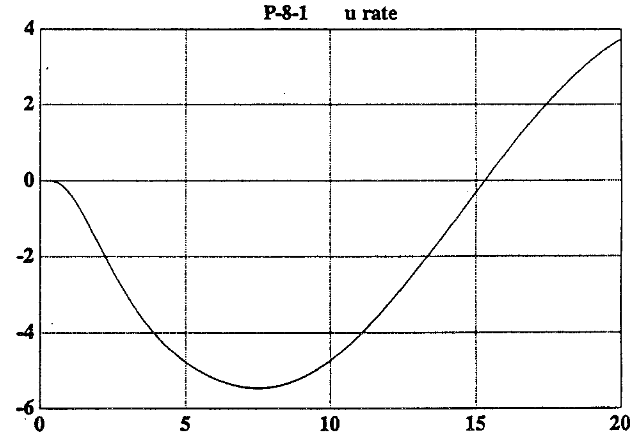

P-7-4 gamma_cg rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

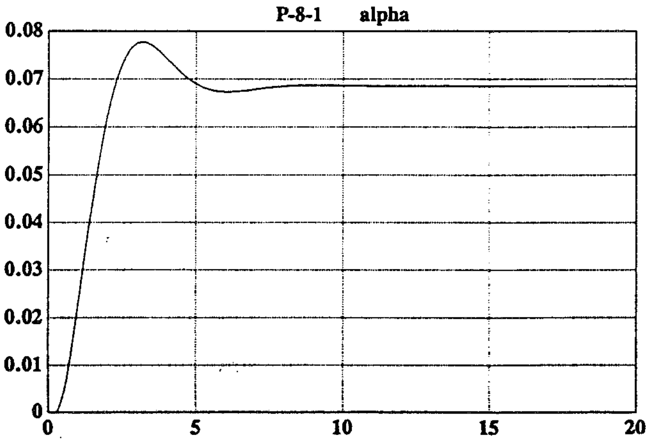

P-7-4 gamma_p
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

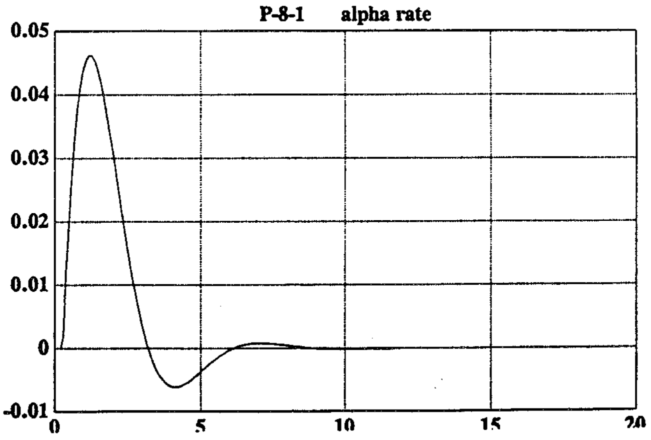

P-7-4 gamma_p rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

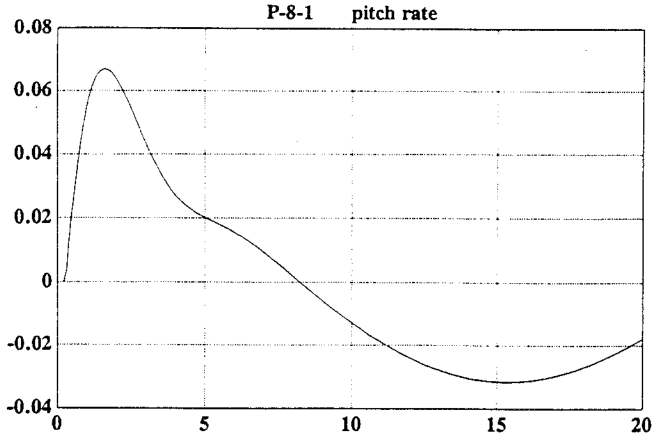

Configuration P-8-1 Alpha, Theta, Gamma_cg

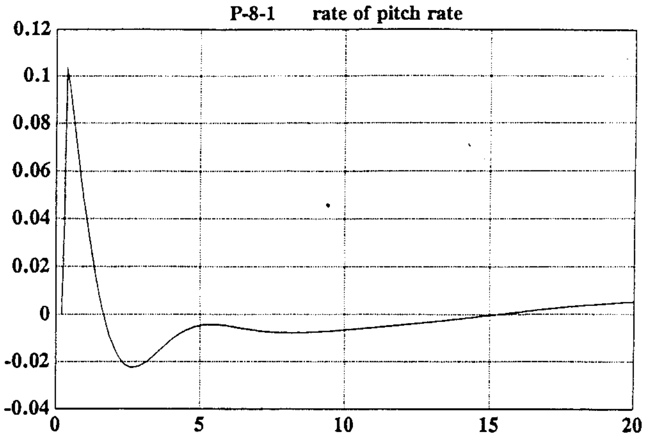

P-8-1 u

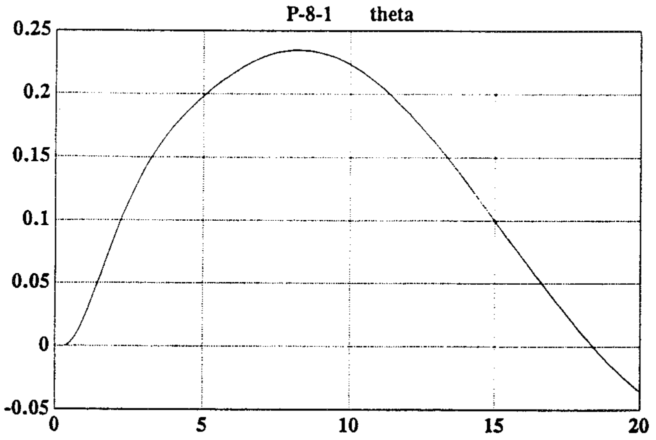

P-8-1 u rate

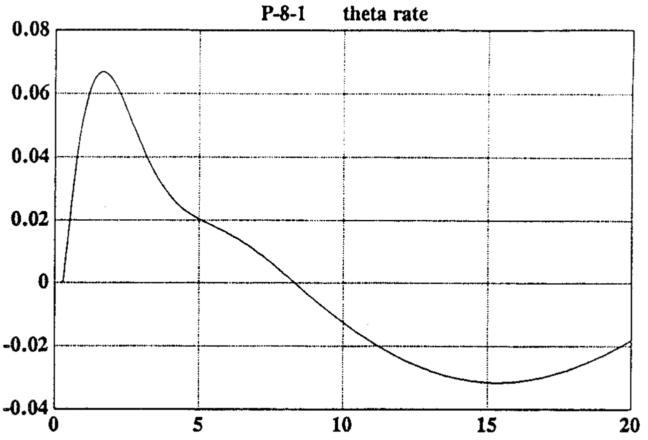

P-8-1 alpha

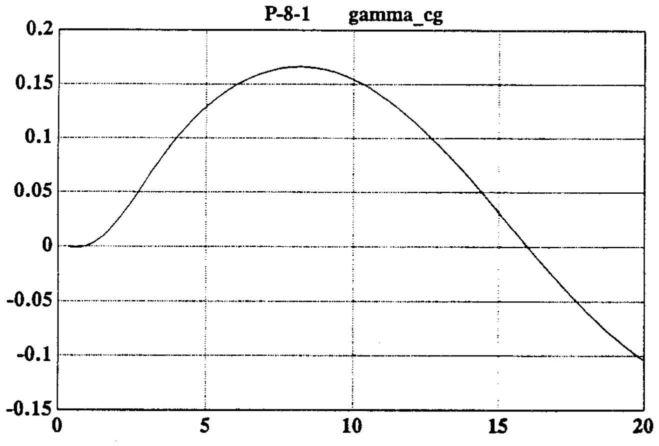

P-8-1 alpha rate

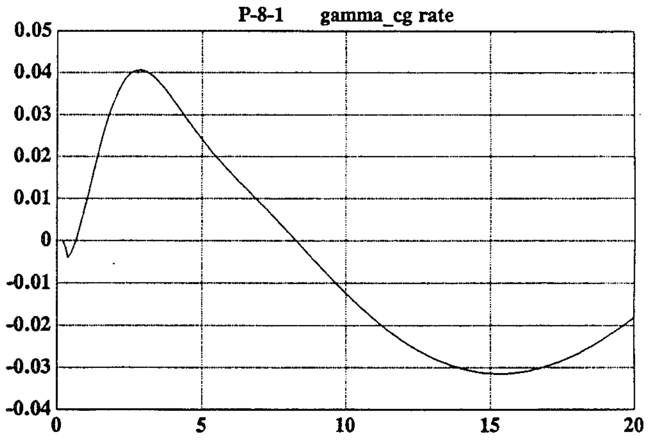

P-8-1 pitch rate

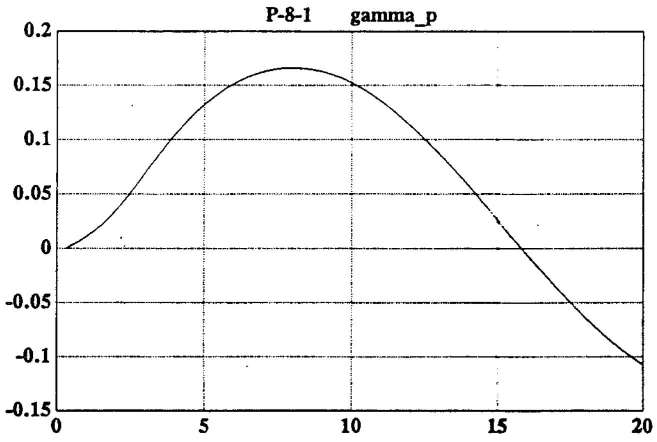

P-8-1 rate of pitch rate

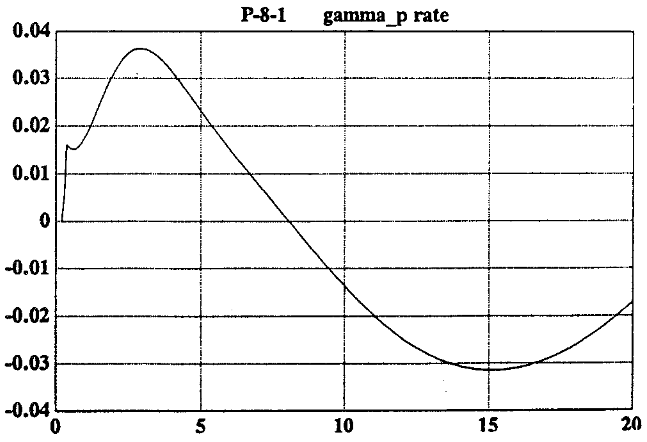

P-8-1 theta

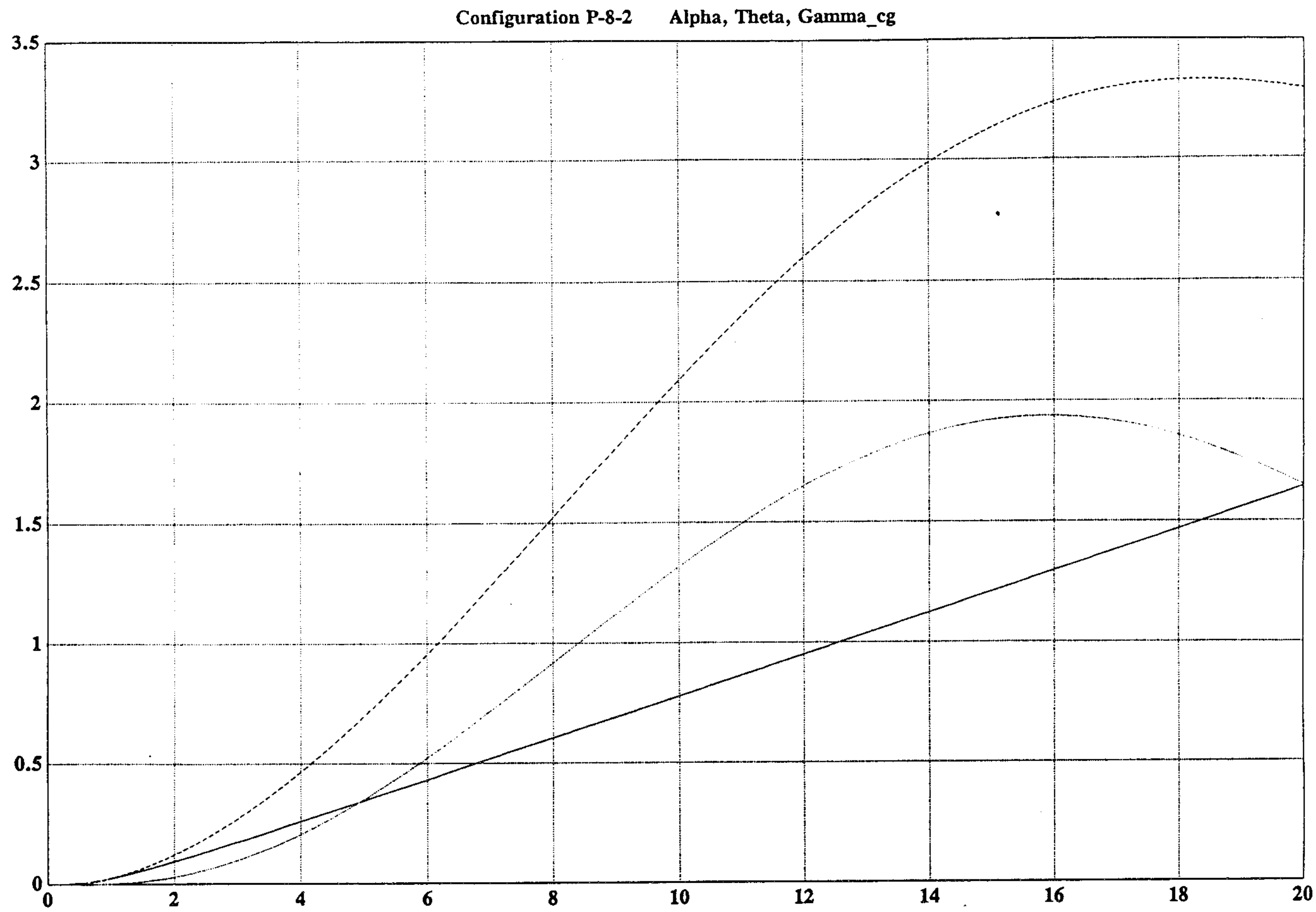

P-8-1 theta rate

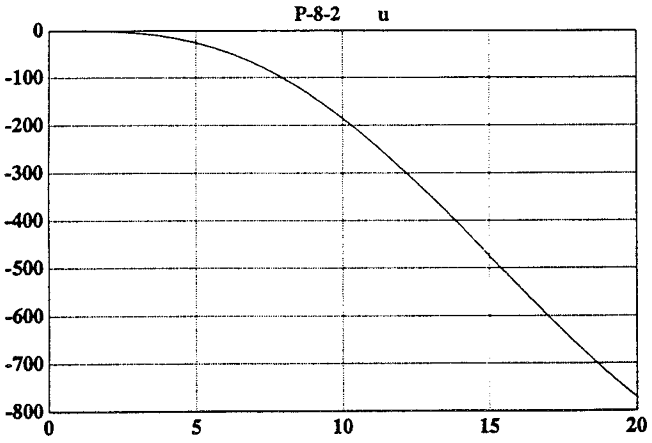

P-8-1 gamma_cg

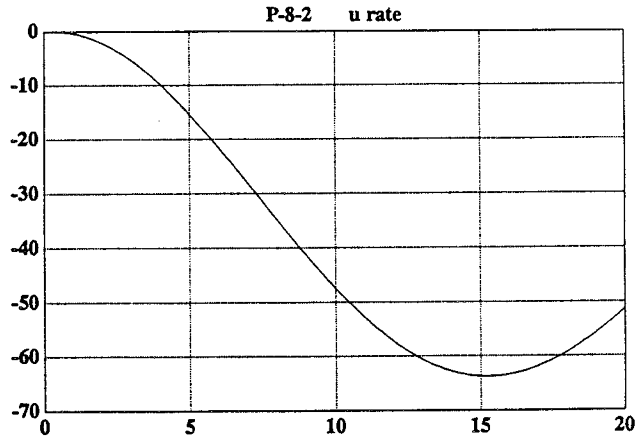

P-8-1 gamma_cg rate

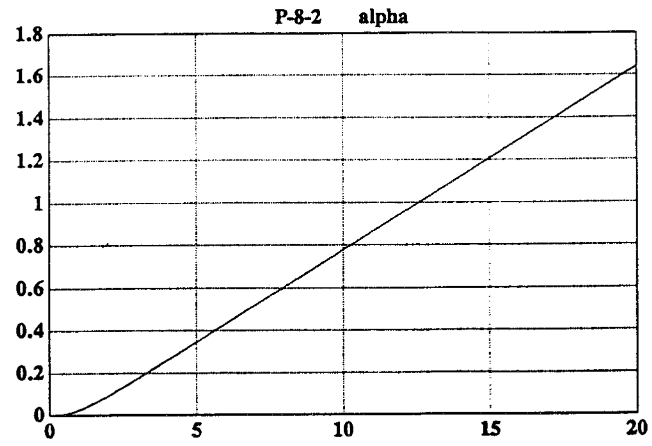

P-8-1 gamma_p

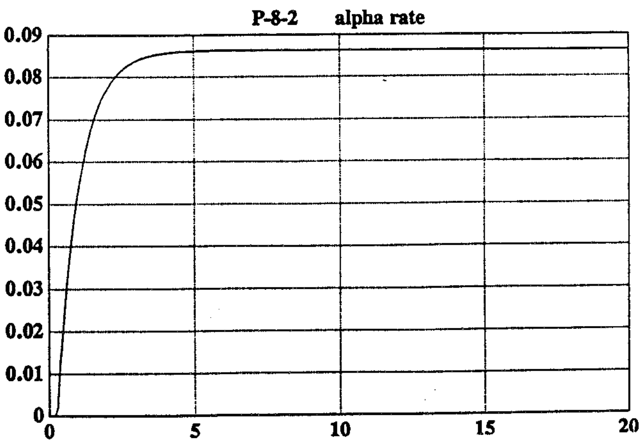

P-8-1 gamma_p rate

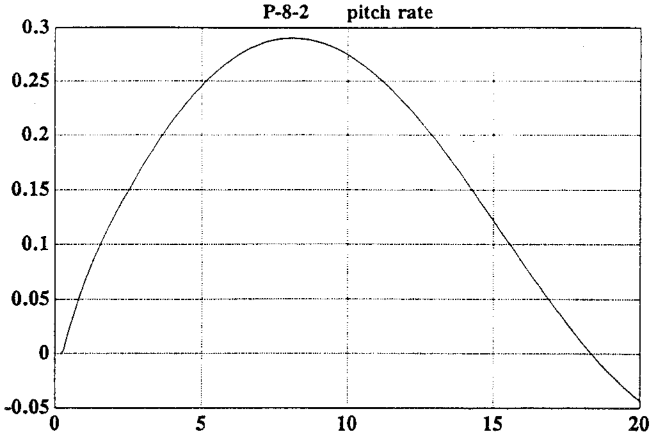

Configuration P-8-2 Alpha, Theta, Gamma_cg

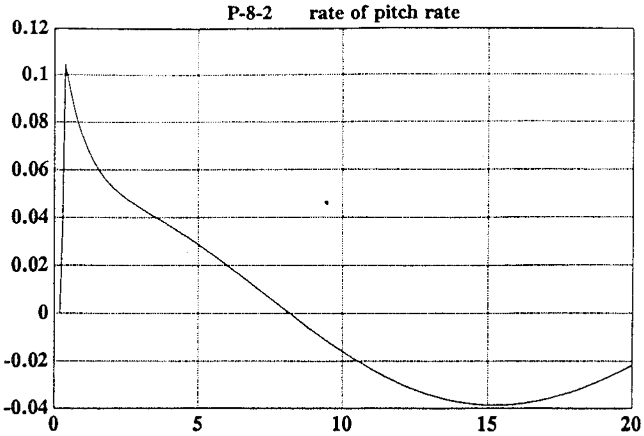

P-8-2 u

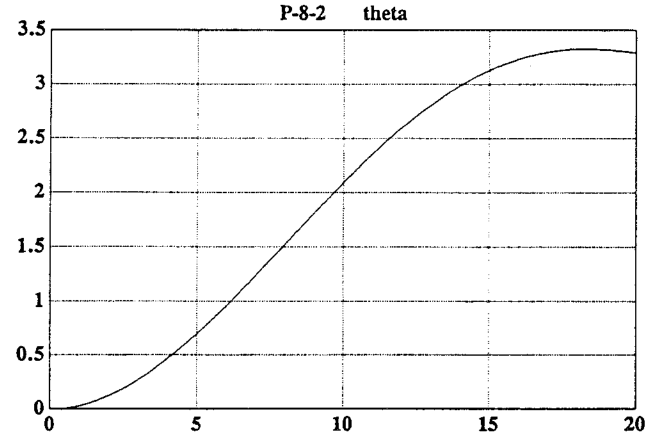

P-8-2 u rate

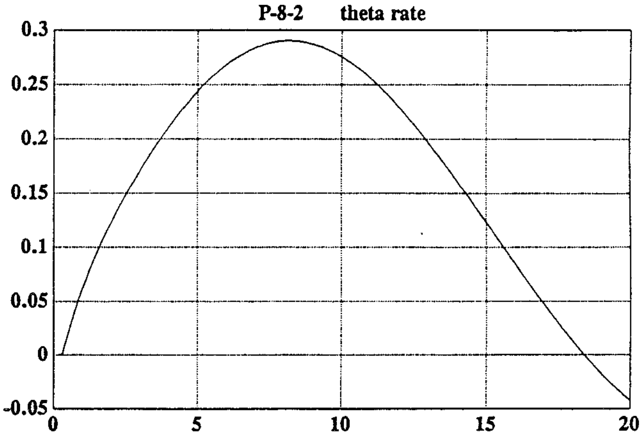

P-8-2 alpha

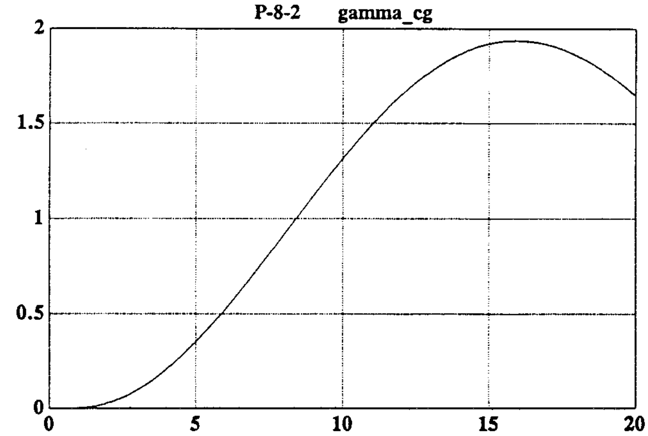

P-8-2 alpha rate

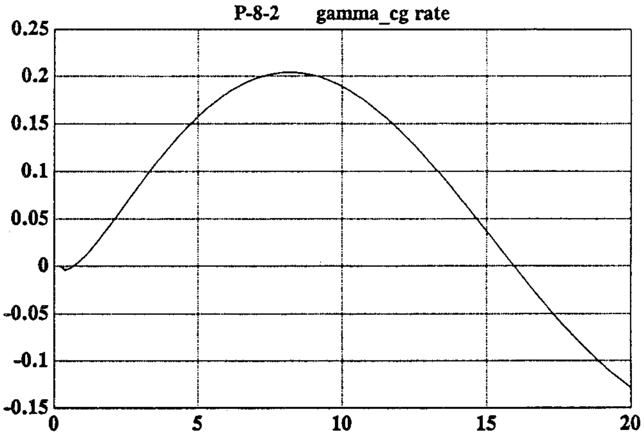

P-8-2 pitch rate

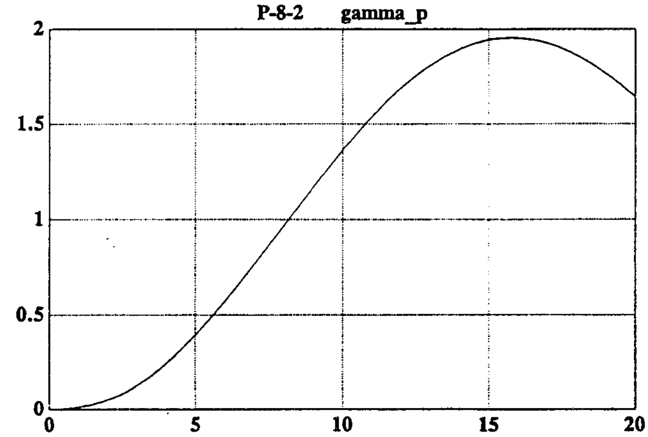

P-8-2 rate of pitch rate

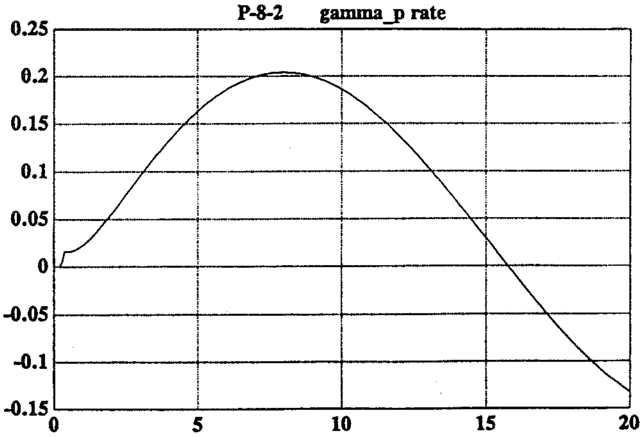

P-8-2 theta

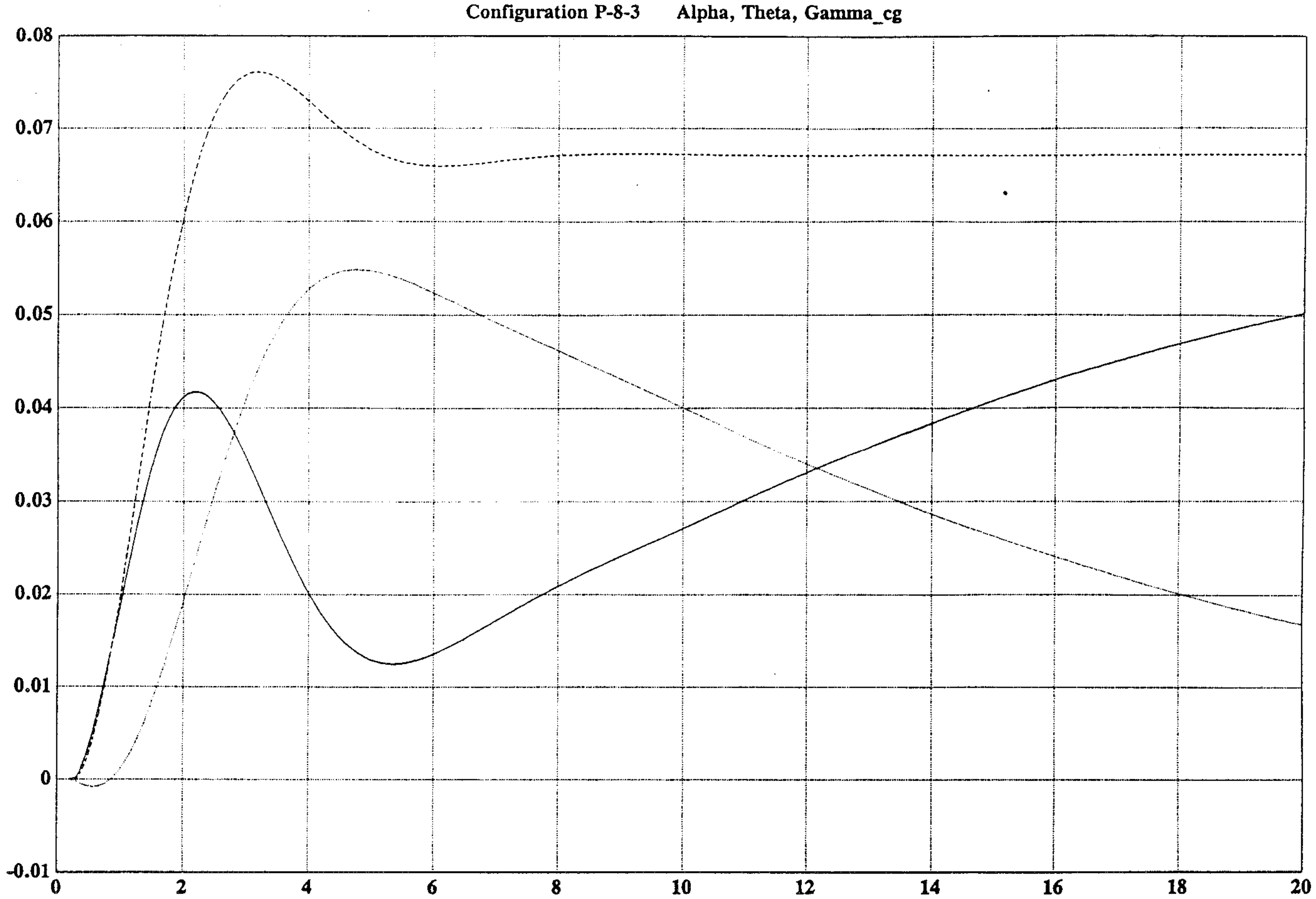

P-8-2 theta rate

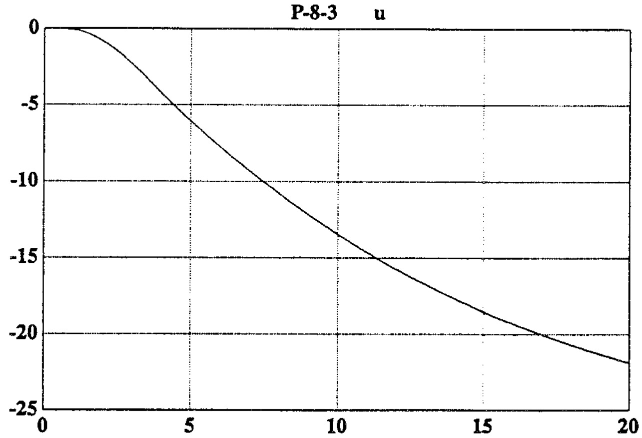

P-8-2 gamma_cg

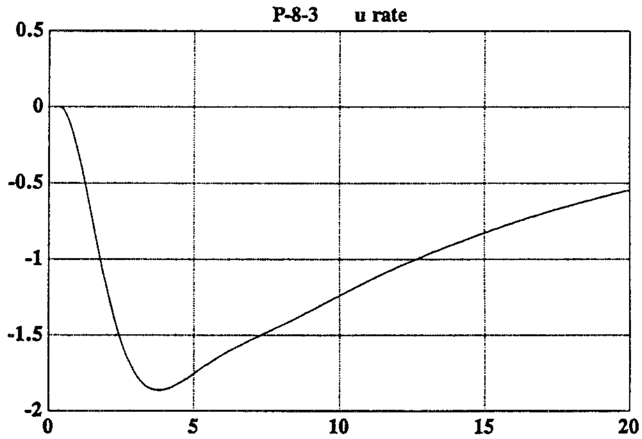

P-8-2 gamma_cg rate

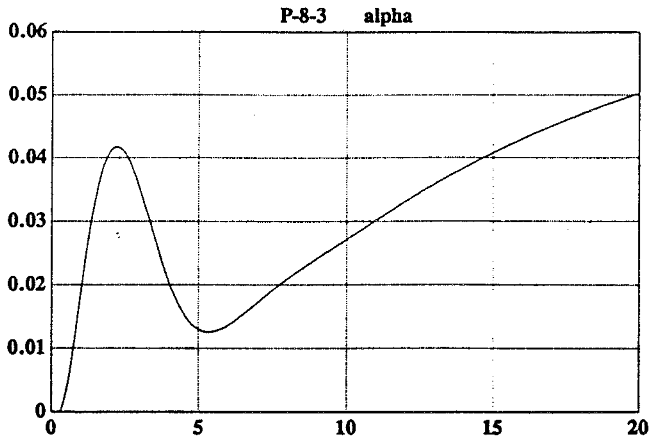

P-8-2 gamma_p

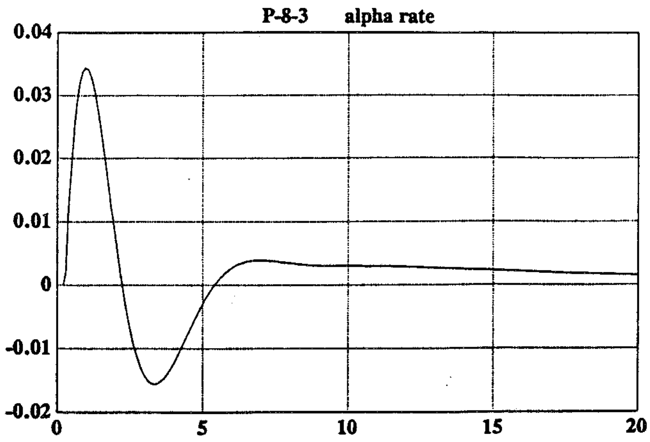

P-8-2 gamma_p rate

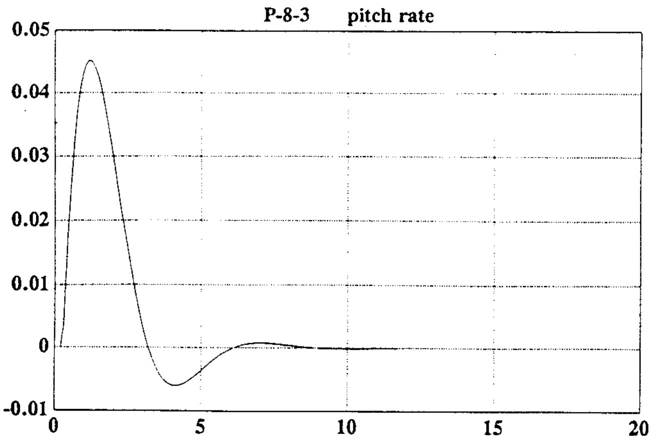

Configuration P-8-3 Alpha, Theta, Gamma_cg

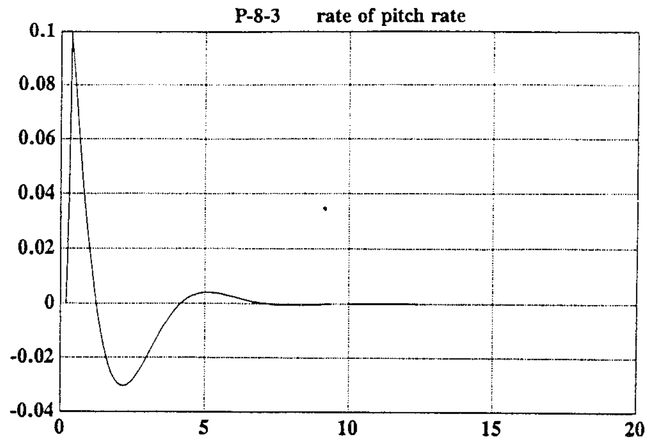

P-8-3 u

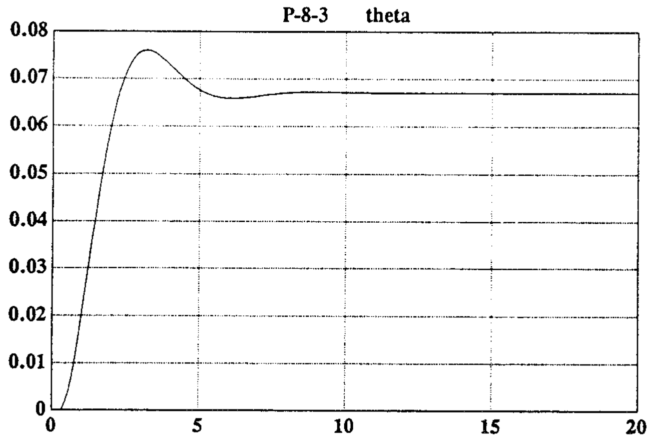

P-8-3 u rate

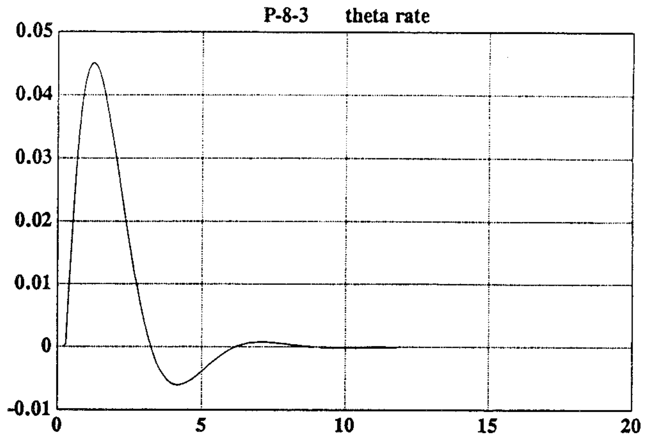

P-8-3 alpha

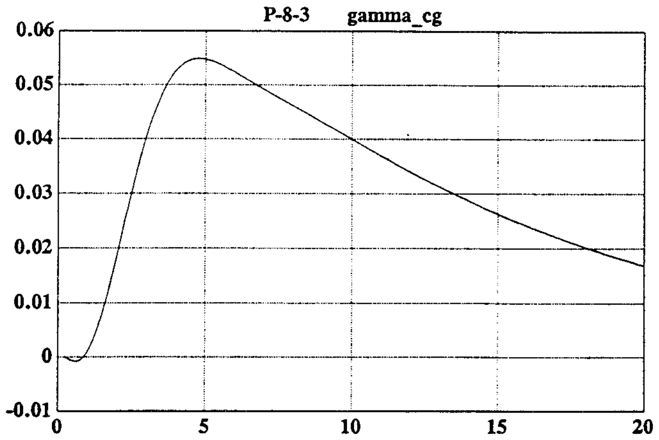

P-8-3 alpha rate

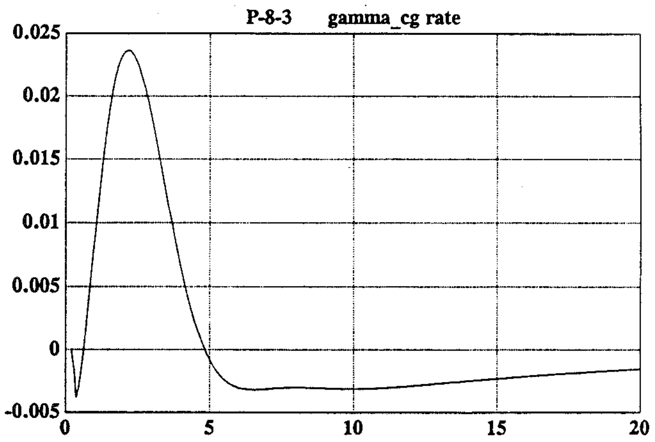

P-8-3 pitch rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

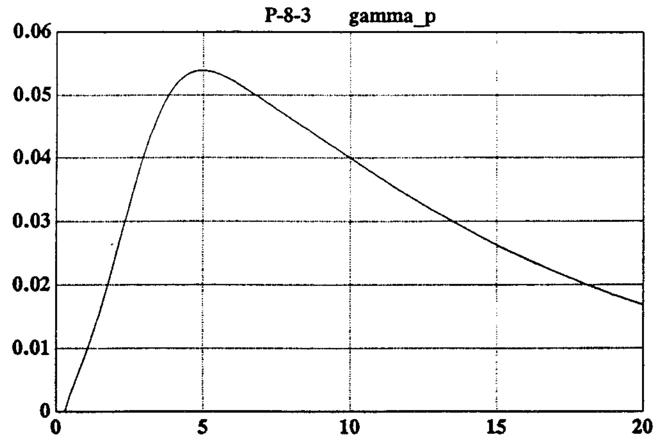

P-8-3 rate of pitch rate
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

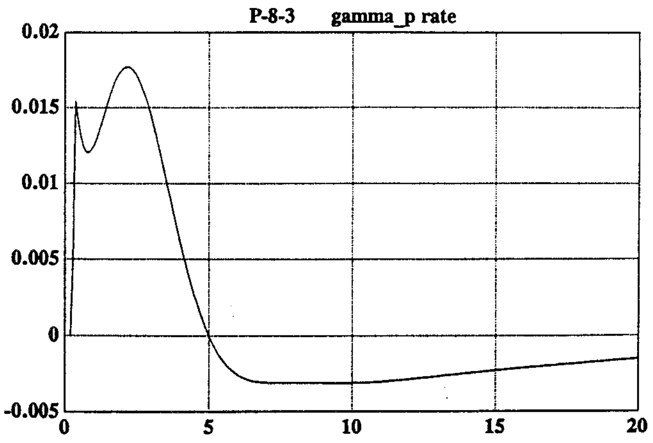

P-8-3 theta
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

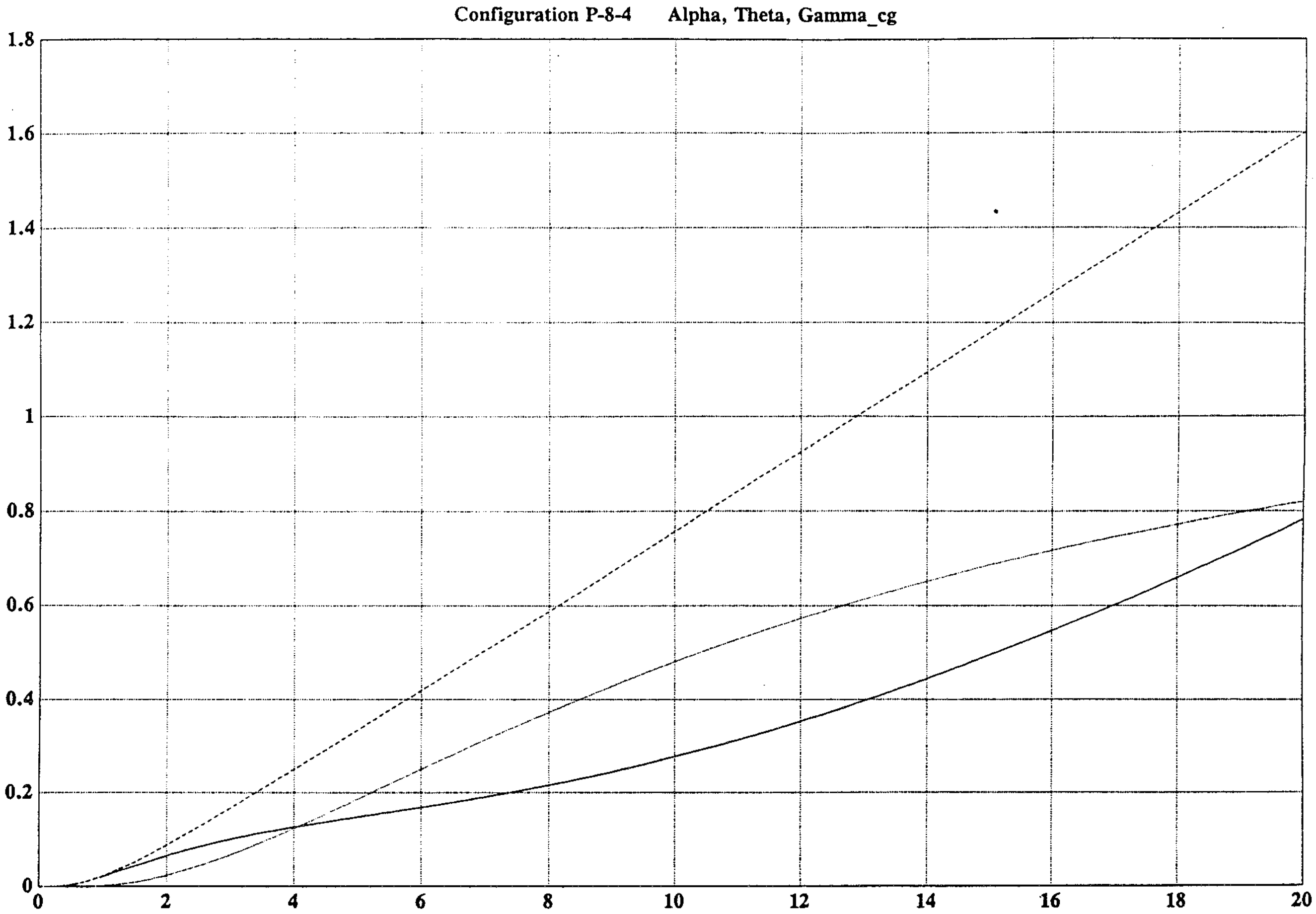

P-8-3 theta rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

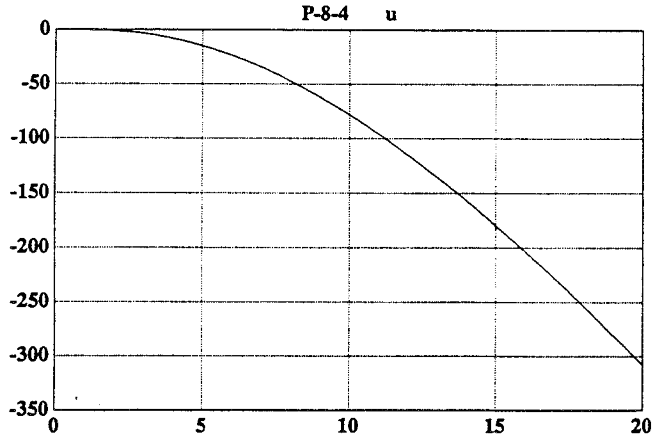

P-8-3 gamma_cg
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

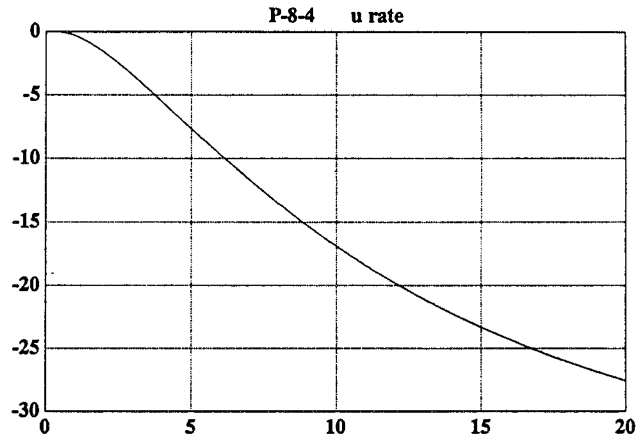

P-8-3 gamma_cg rate
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
5
10
15
20

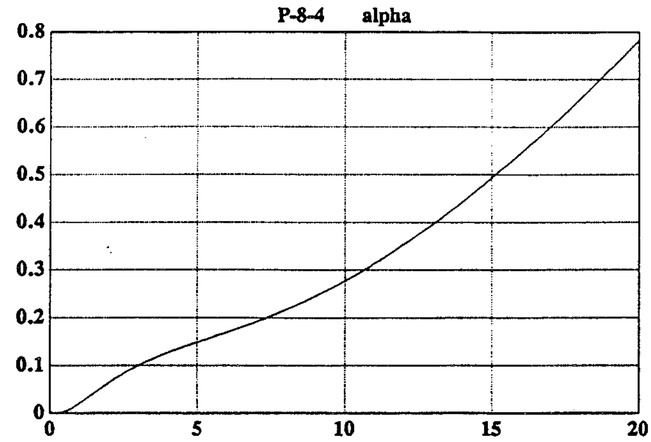

P-8-3 gamma_p
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

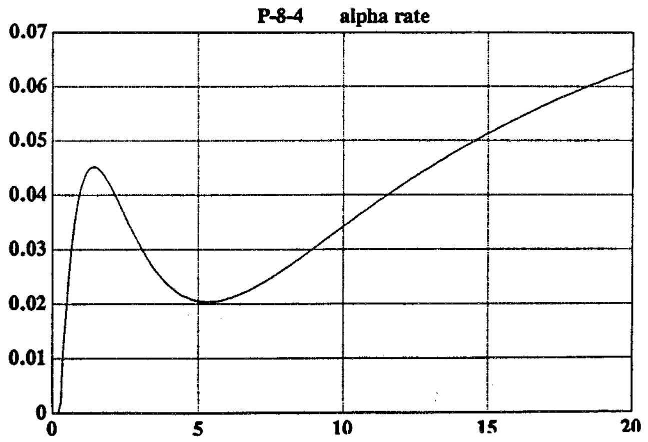

P-8-3 gamma_p rate
0.02
0.015
0.01
0.005
0
-0.005
0
5
10
15
20

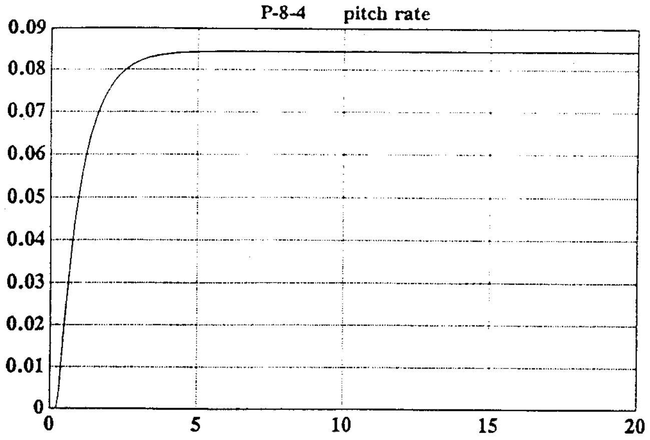

Configuration P-8-4 Alpha, Theta, Gamma_cg

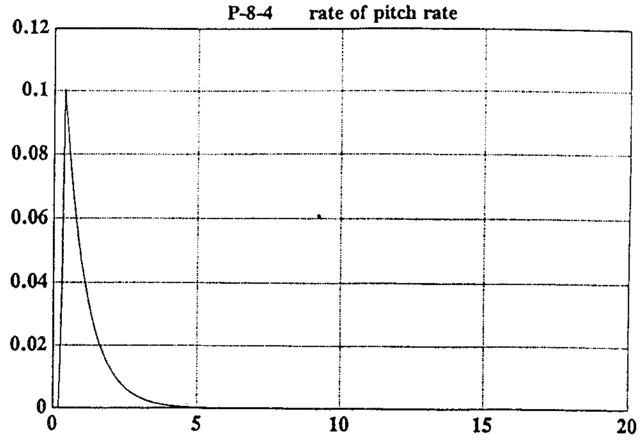

P-8-4 u

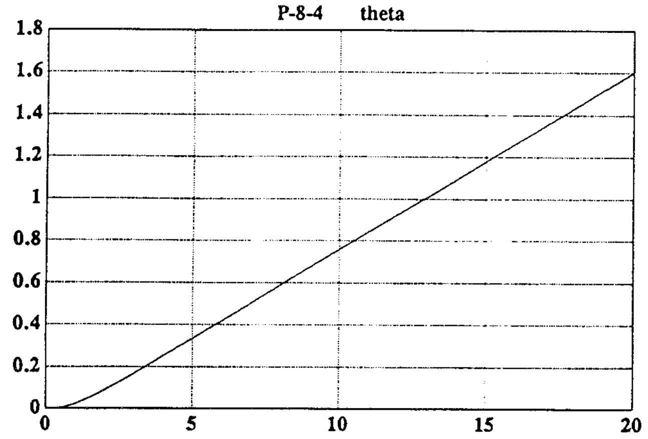

P-8-4 u rate

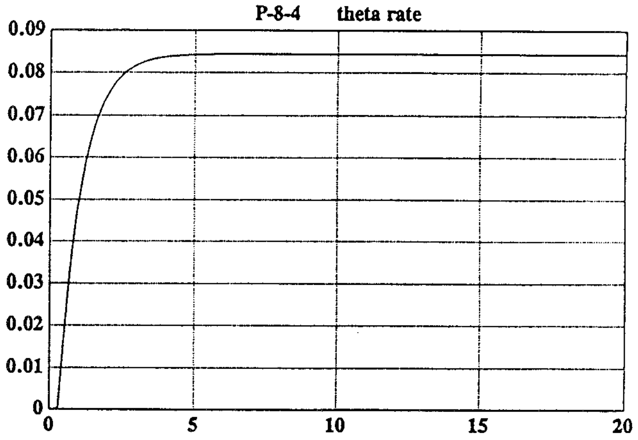

P-8-4 alpha

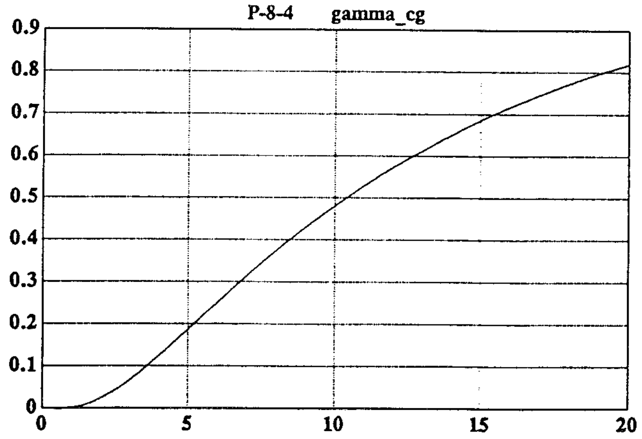

P-8-4 alpha rate

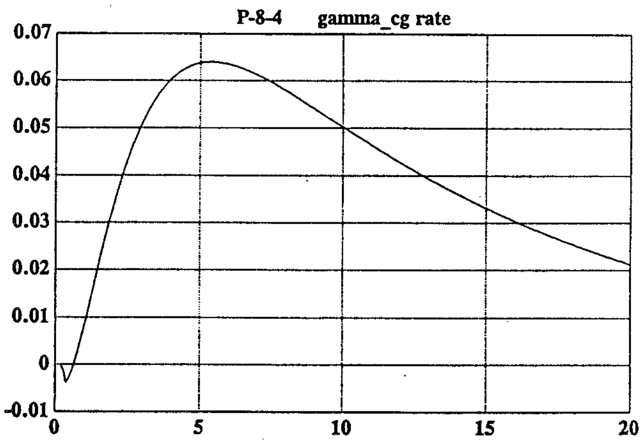

P-8-4 pitch rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

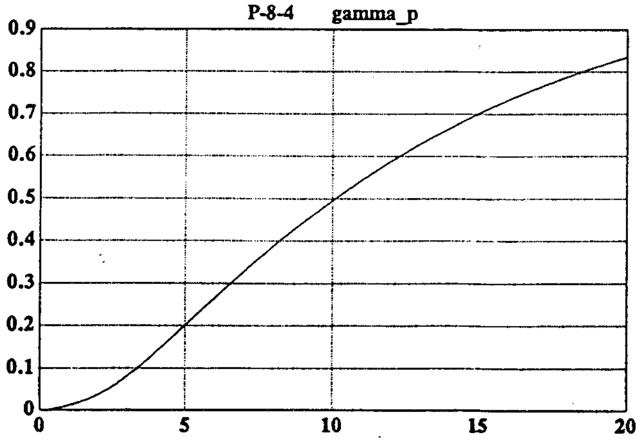

P-8-4 rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

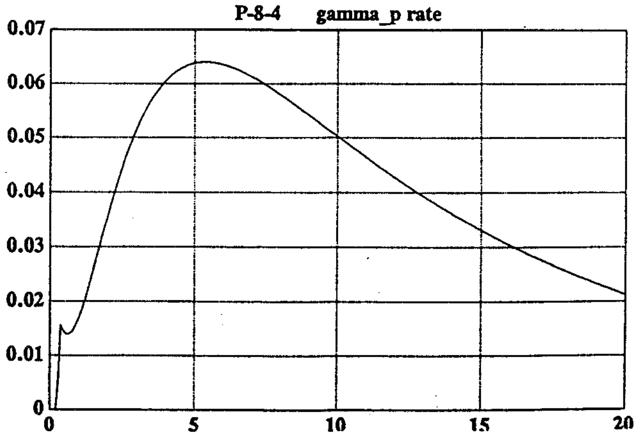

P-8-4 theta
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20

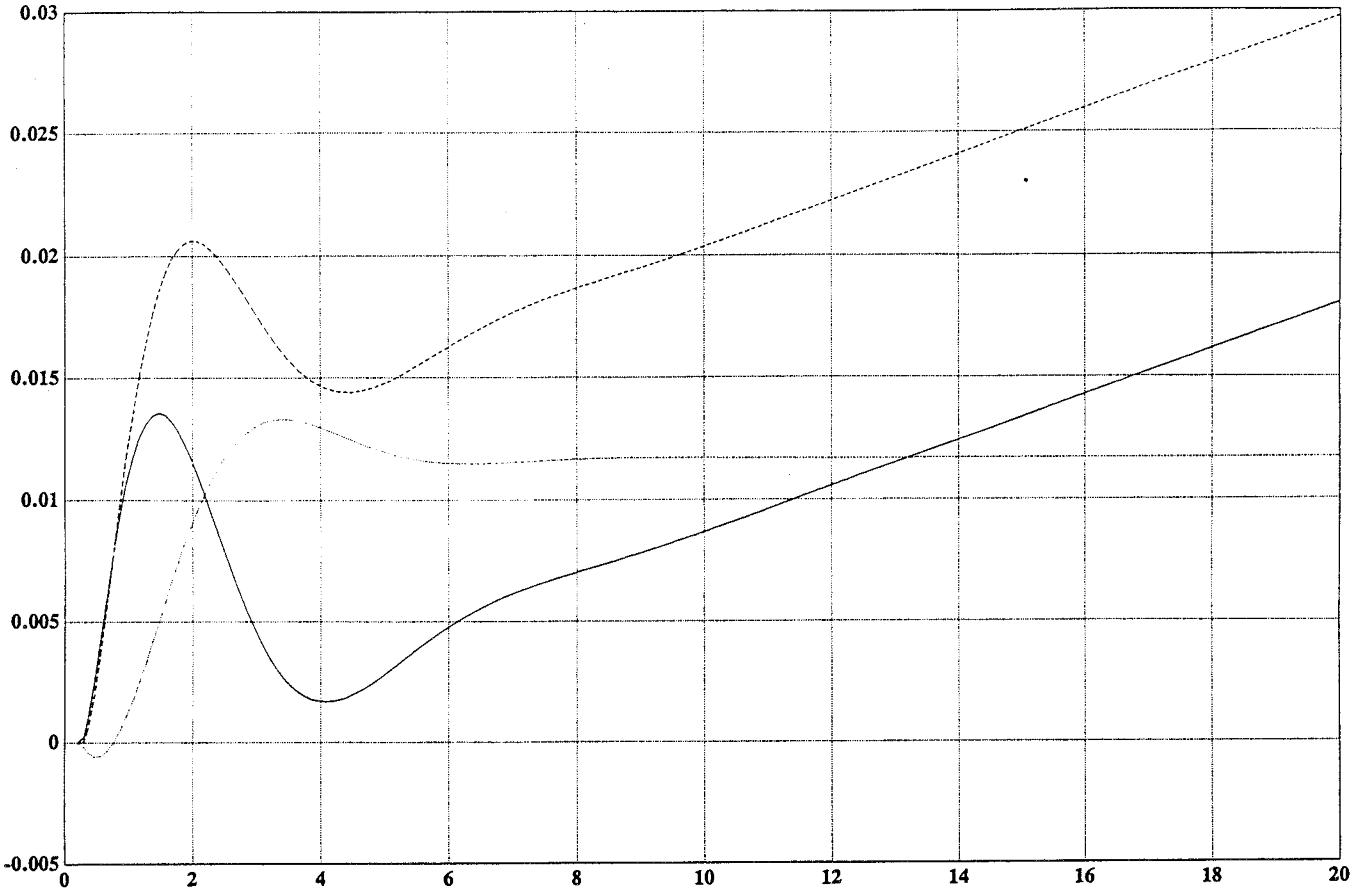

P-8-4 theta rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

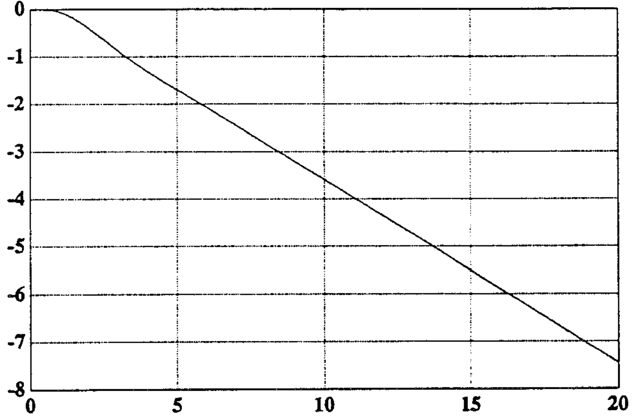

P-8-4 gamma_cg
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

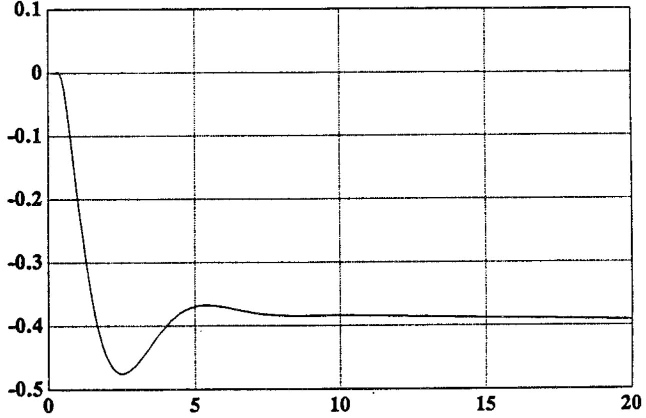

P-8-4 gamma_cg rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

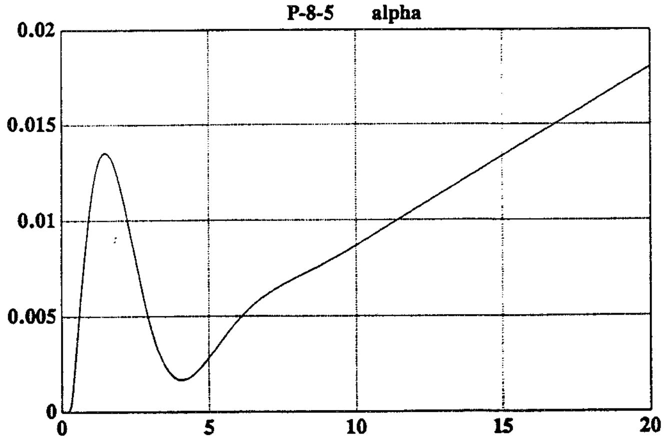

P-8-4 gamma_p
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

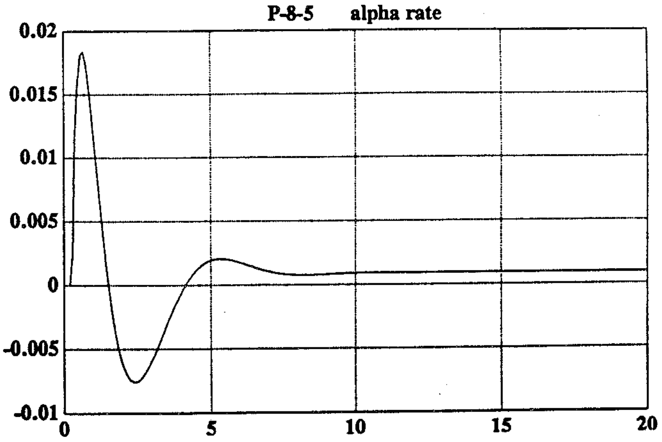

P-8-4 gamma_p rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

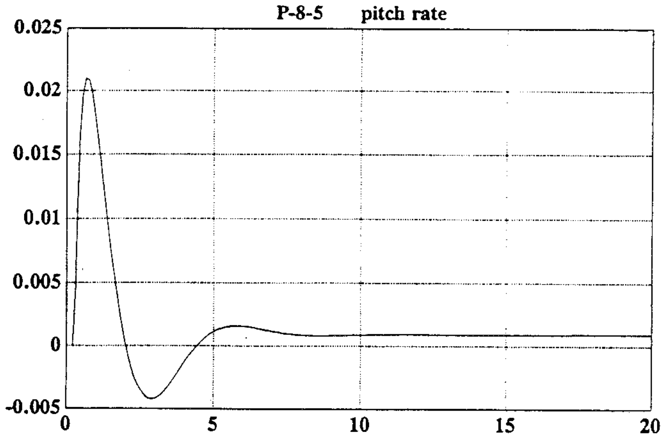

Configuration P-8-5 Alpha, Theta, Gamma_cg

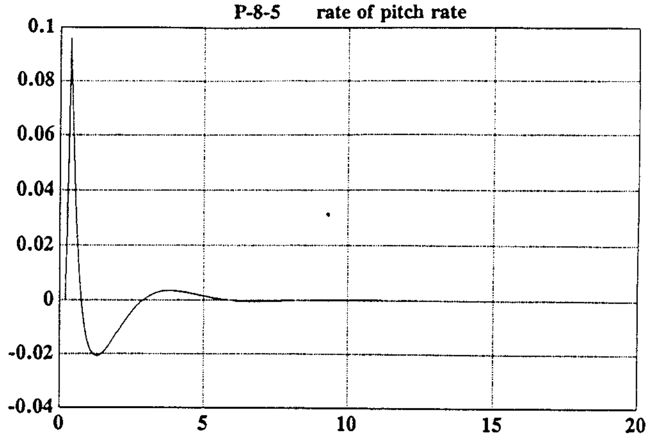

P-8-5 u

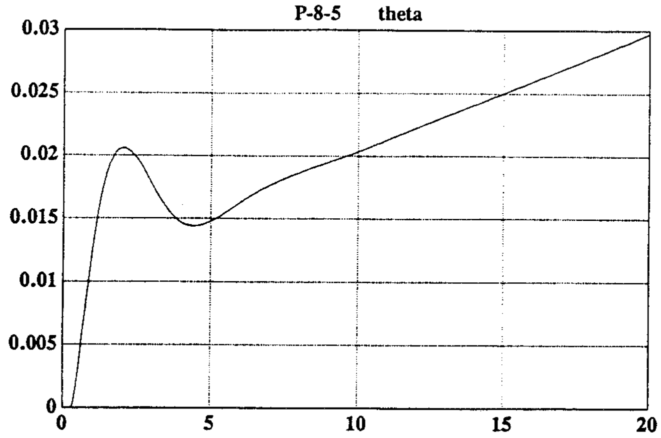

P-8-5 u rate

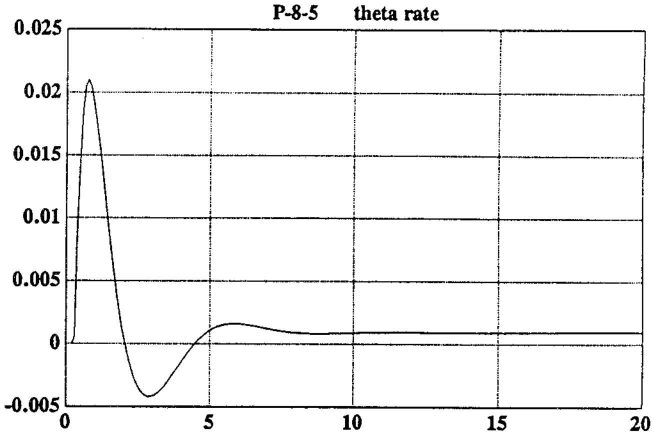

P-8-5 alpha

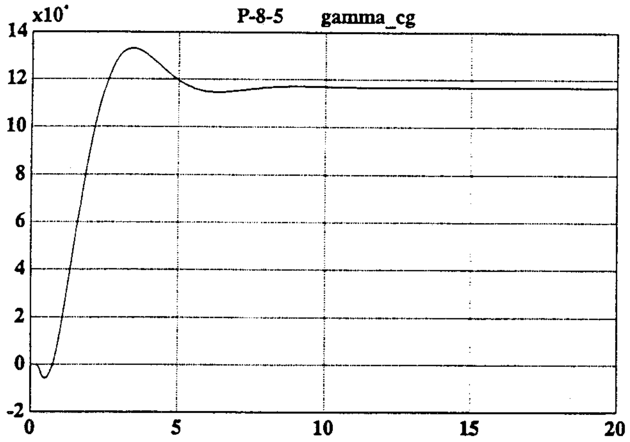

P-8-5 alpha rate

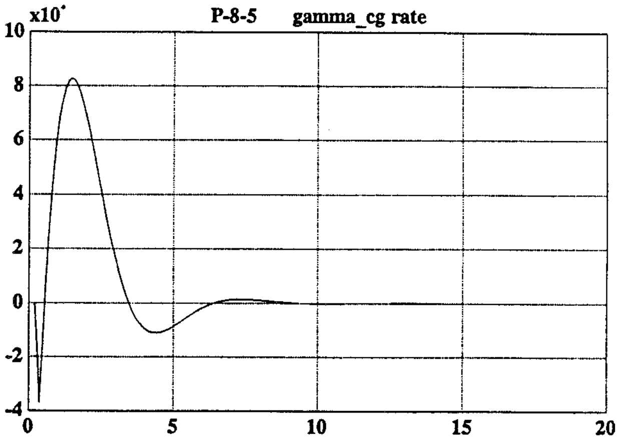

P-8-5 pitch rate

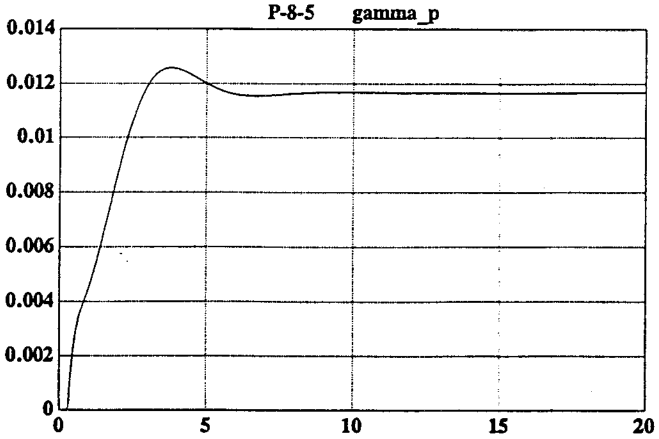

P-8-5 rate of pitch rate

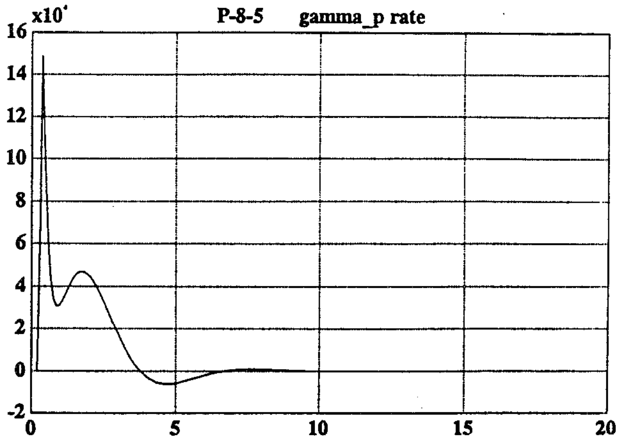

P-8-5 theta

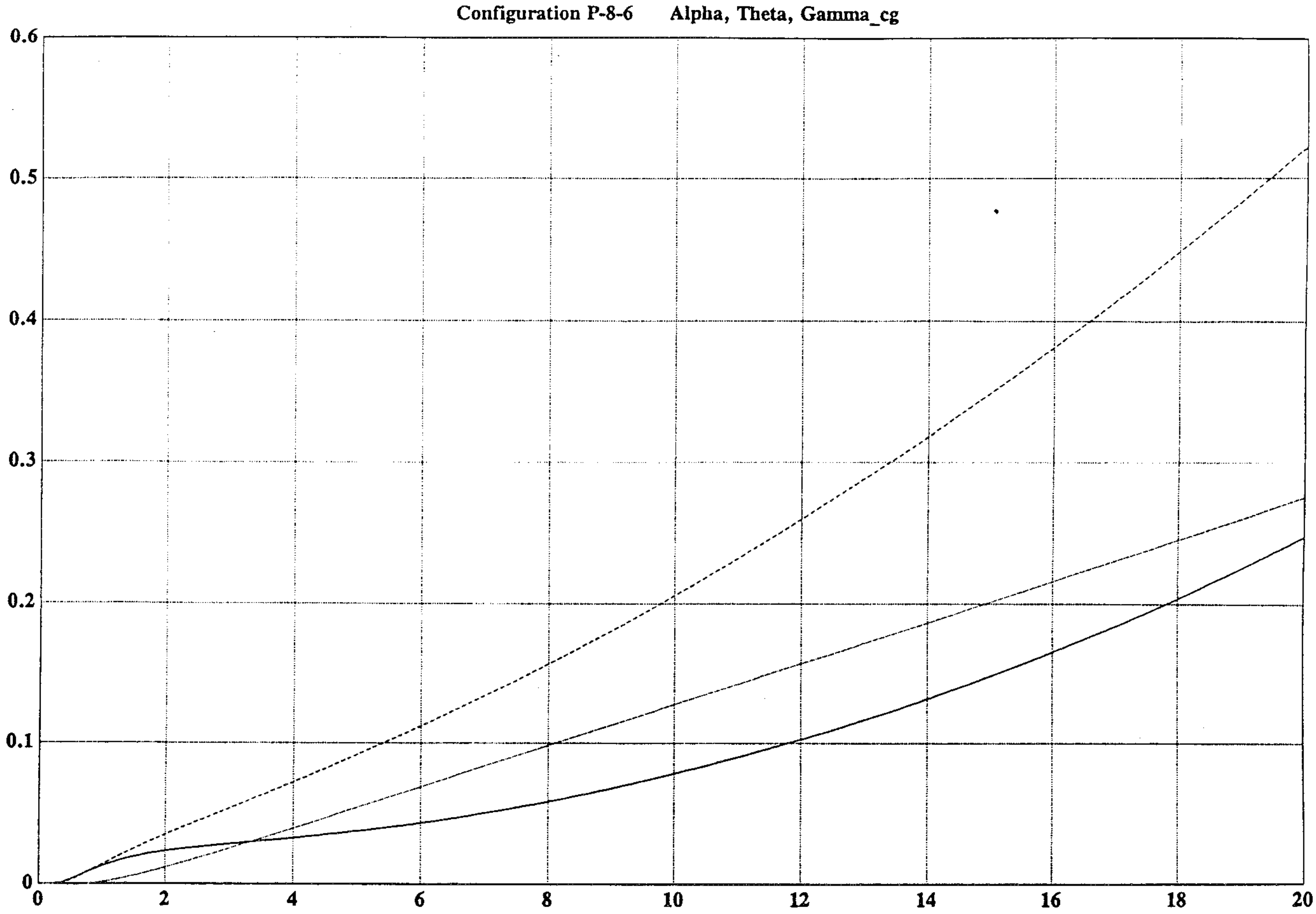

P-8-5 theta rate

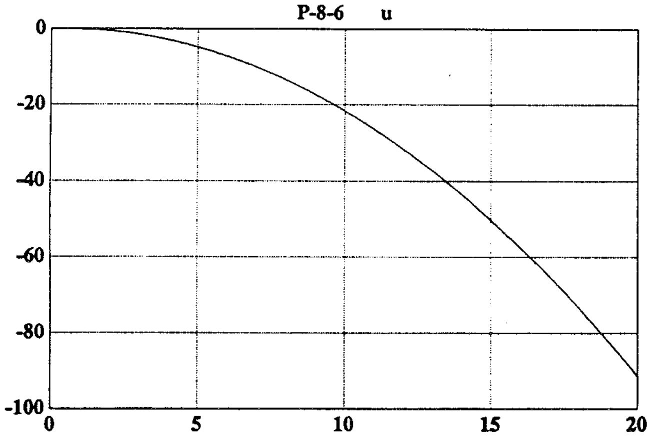

P-8-5 gamma_cg

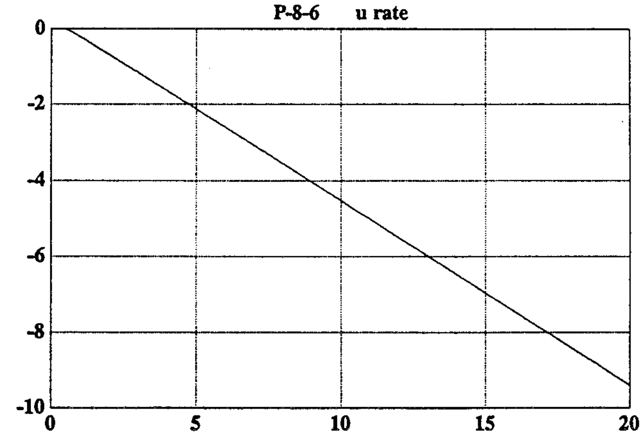

P-8-5 gamma_cg rate

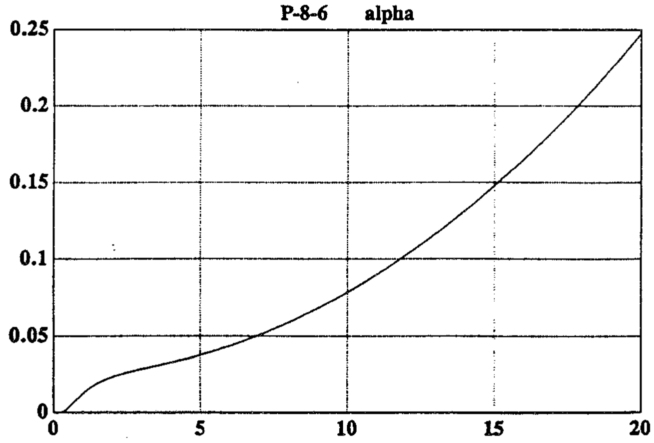

P-8-5 gamma_p

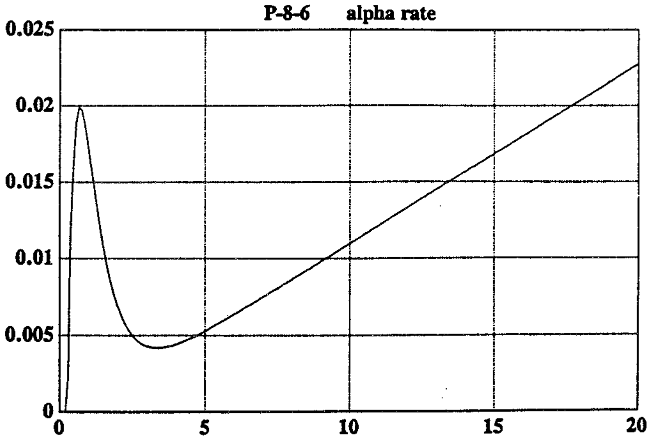

P-8-5 gamma_p rate

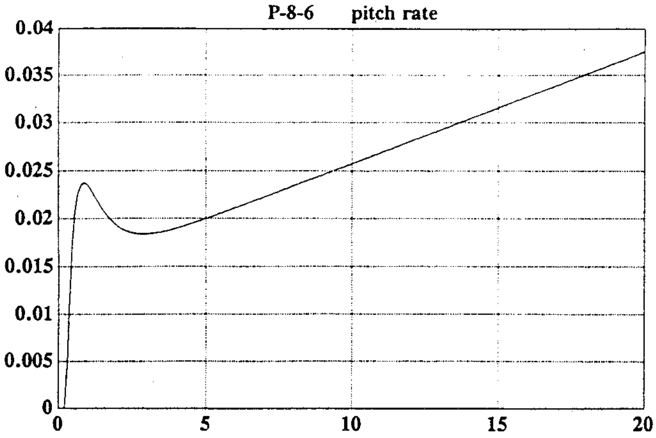

Configuration P-8-6 Alpha, Theta, Gamma_cg

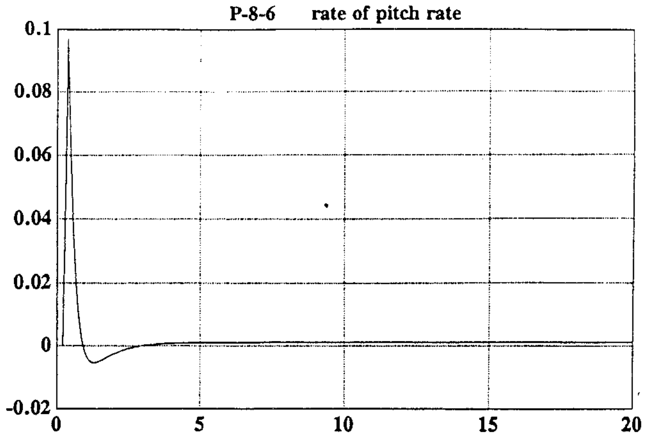

P-8-6 u

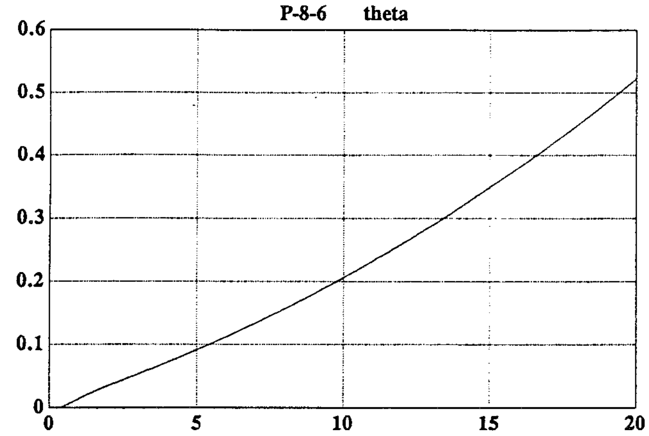

P-8-6 u rate

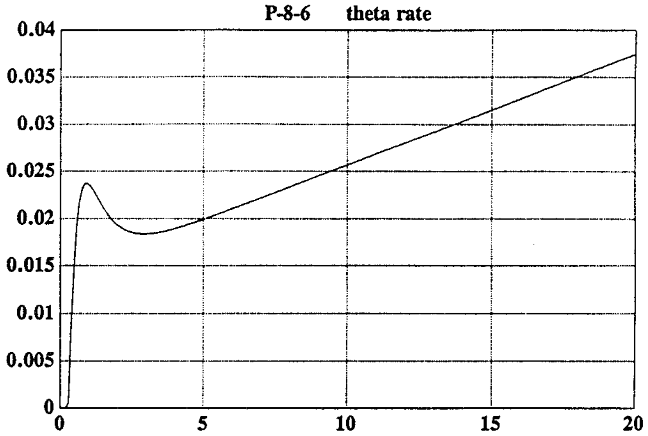

P-8-6 alpha

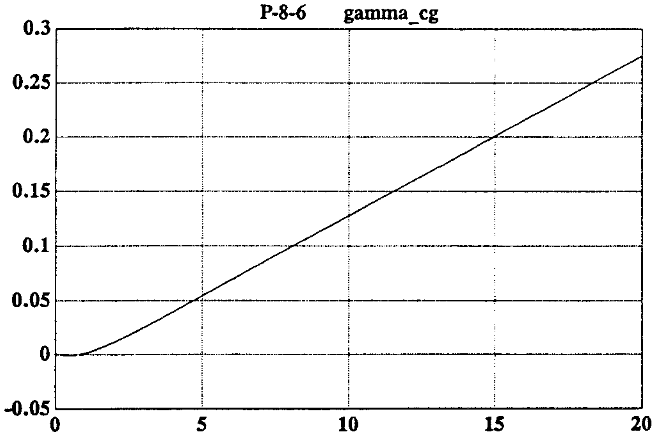

P-8-6 alpha rate

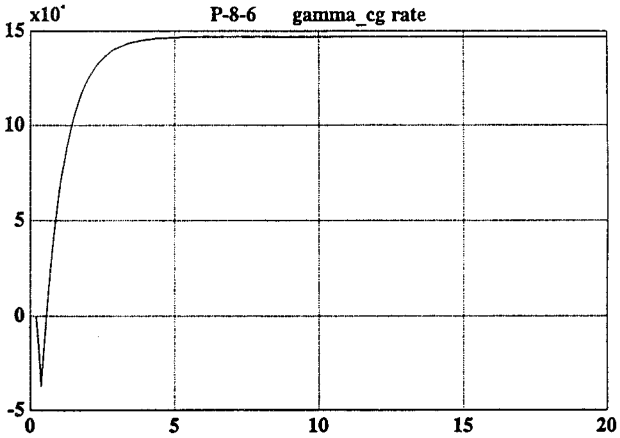

P-8-6 pitch rate
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

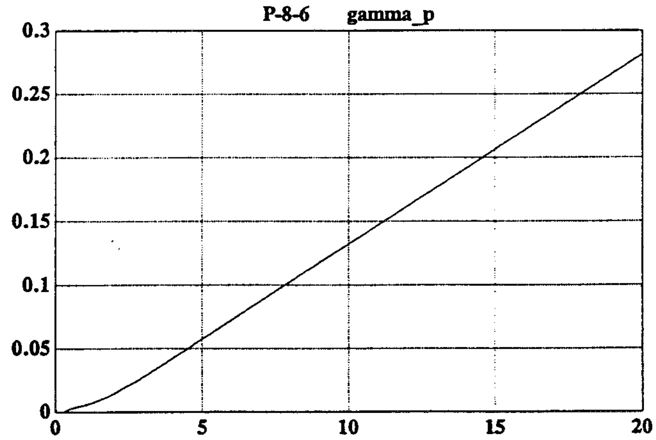

P-8-6 rate of pitch rate
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
5
10
15
20

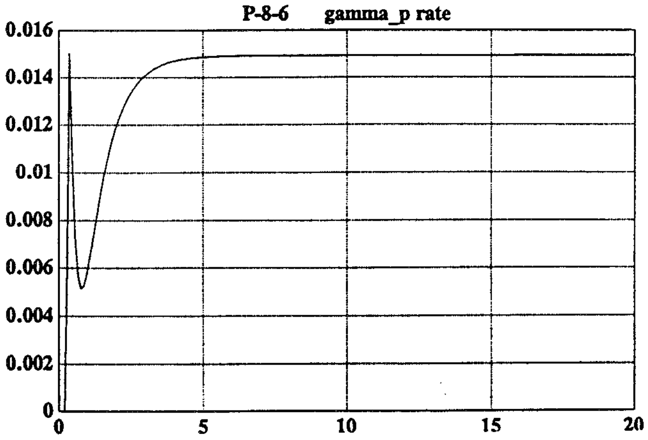

P-8-6 theta
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

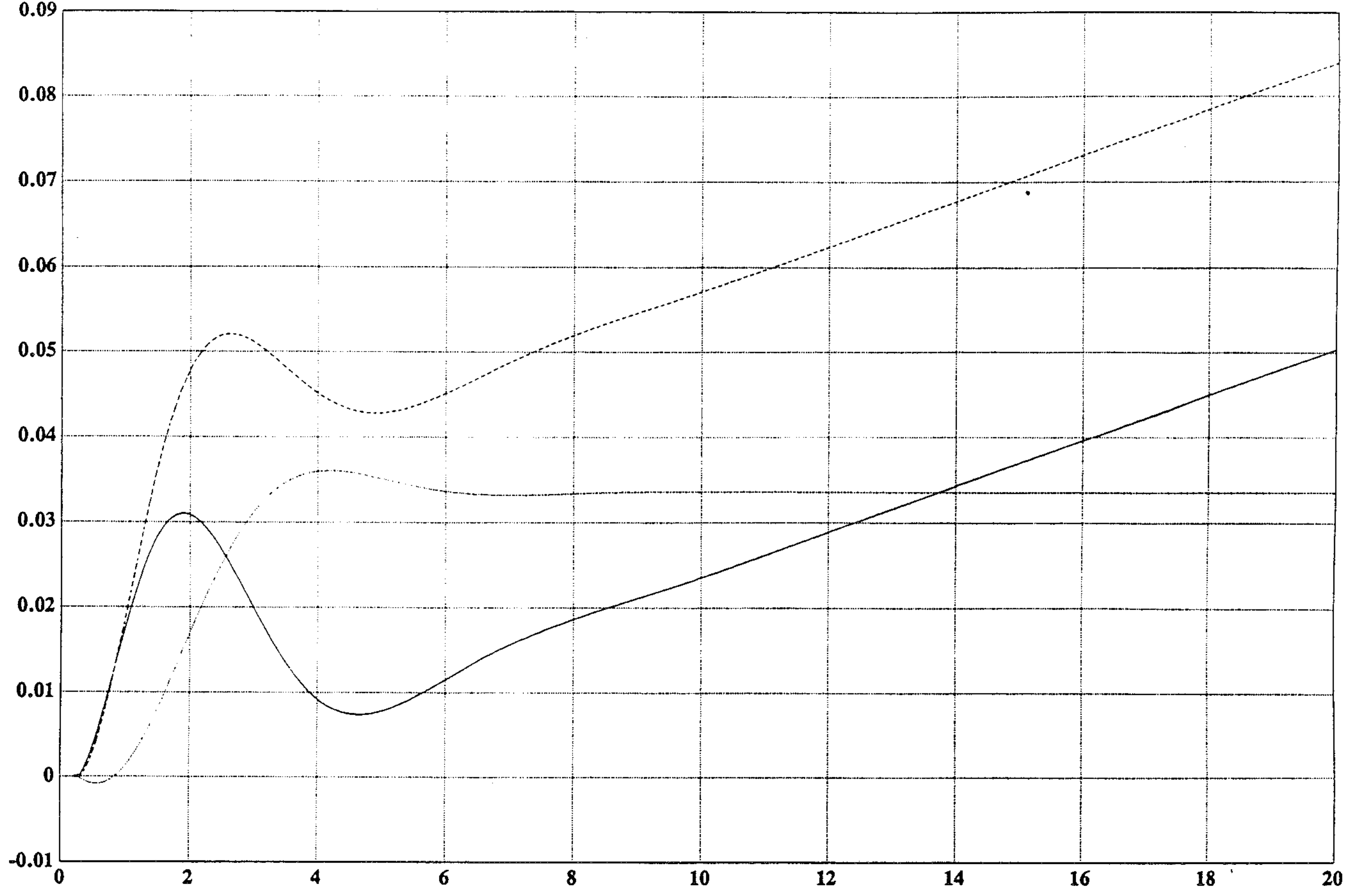

P-8-6 theta rate
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

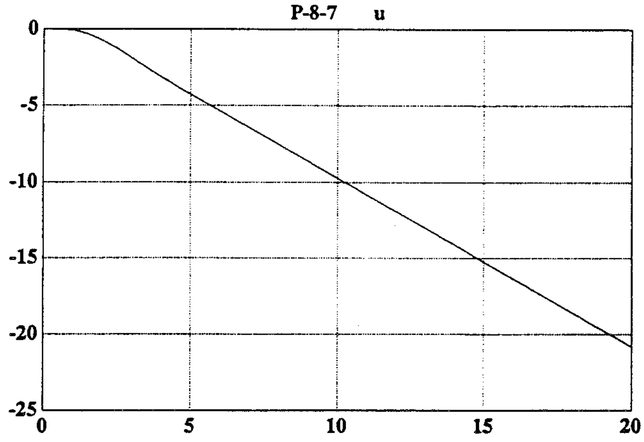

P-8-6 gamma_cg
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
15
20

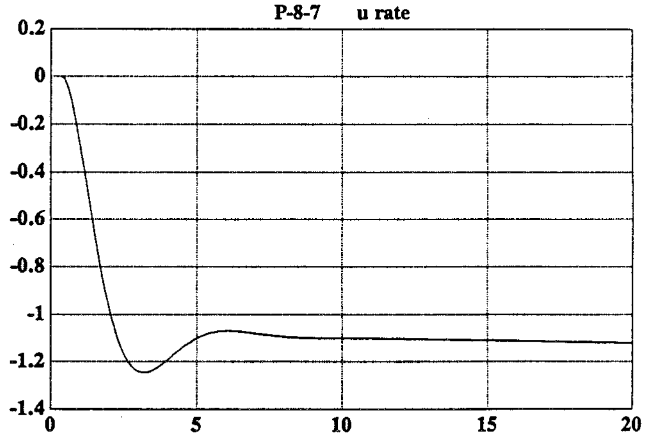

x10
P-8-6 gamma_cg rate
15
10
5
0
-5
0
5
10
15
20

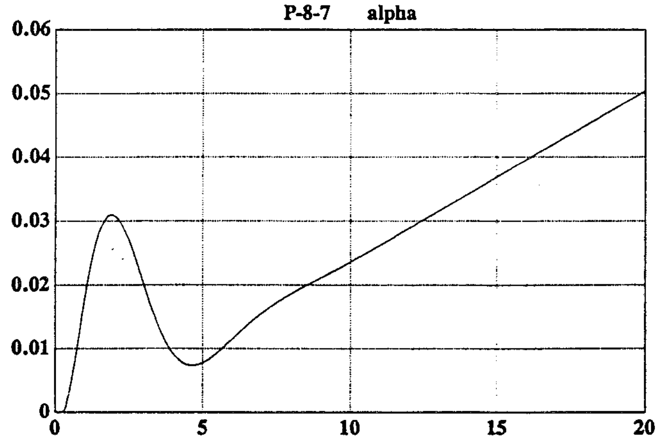

P-8-6 gamma_p
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20

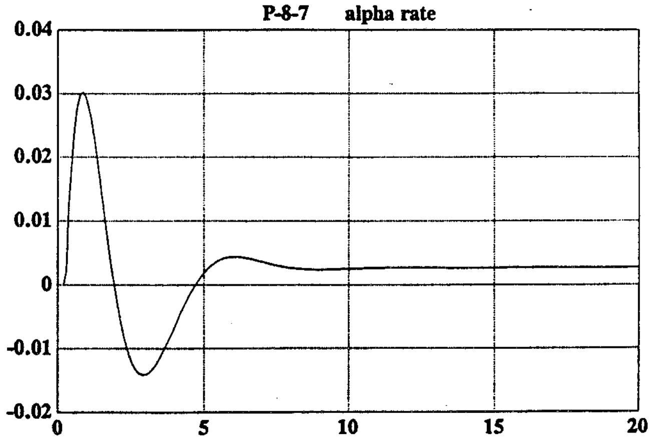

P-8-6 gamma_p rate
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
15
20

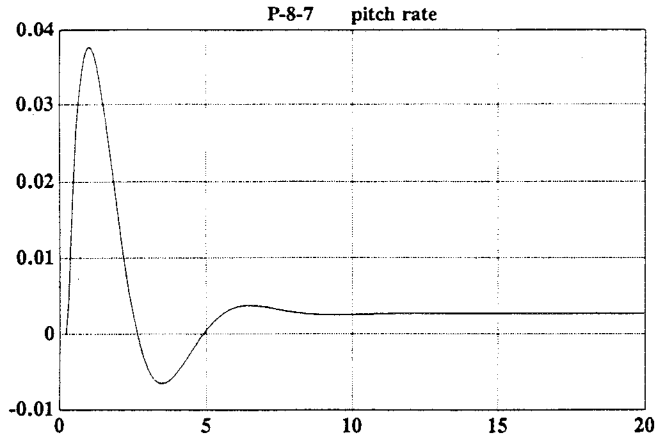

Configuration P-8-7 Alpha, Theta, Gamma_cg

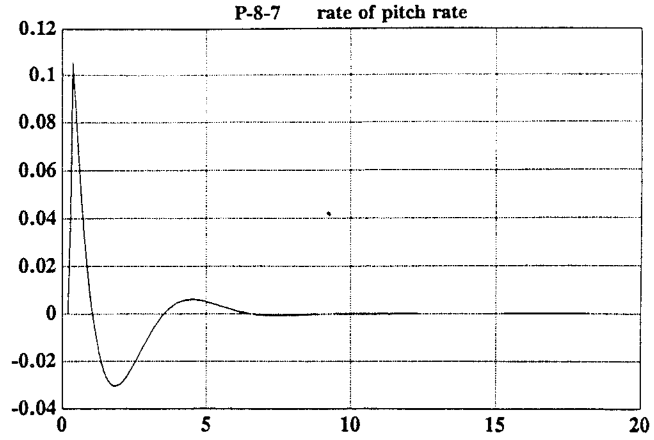

P-8-7 u

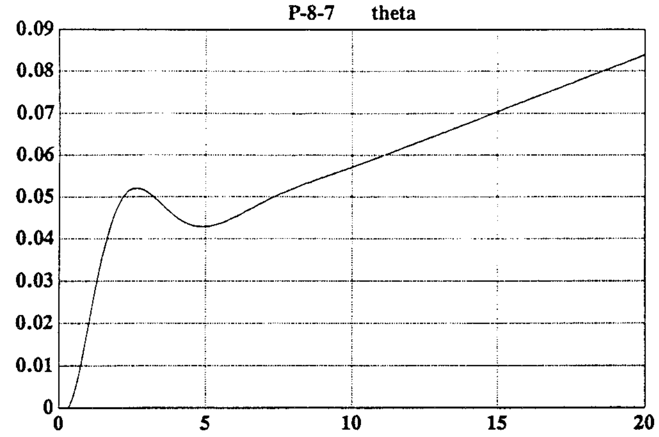

P-8-7 u rate

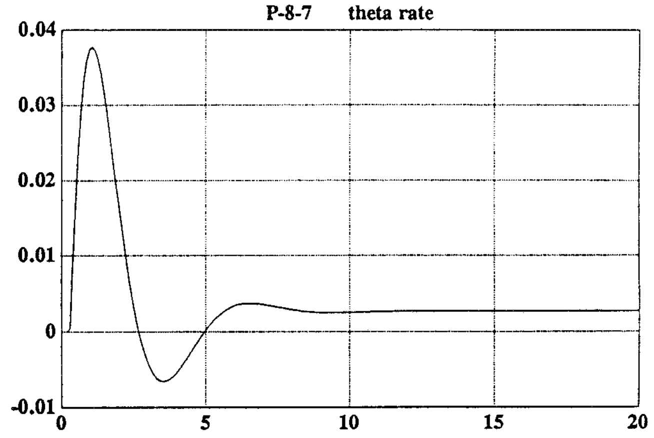

P-8-7 alpha

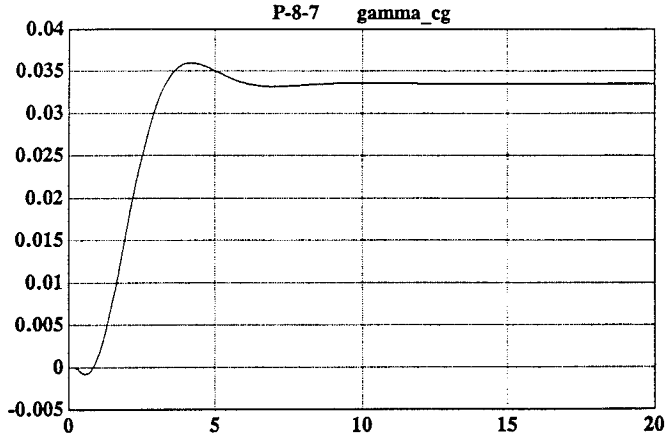

P-8-7 alpha rate

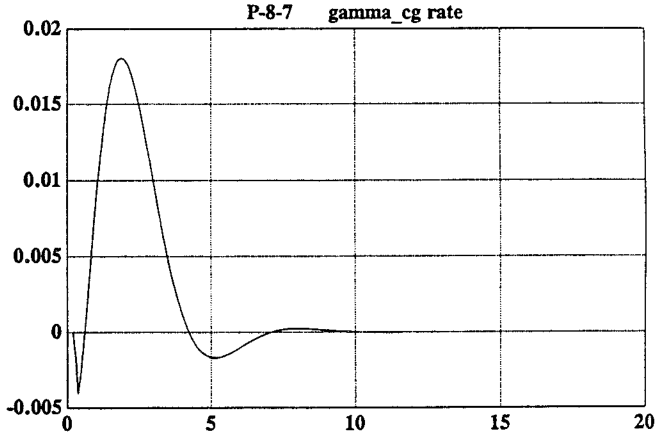

P-8-7 pitch rate

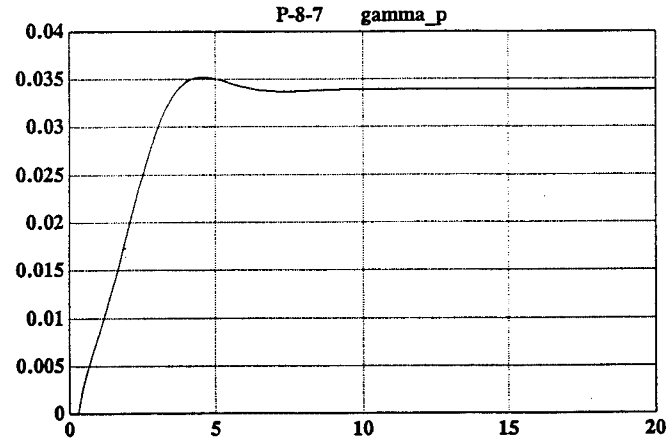

P-8-7 rate of pitch rate

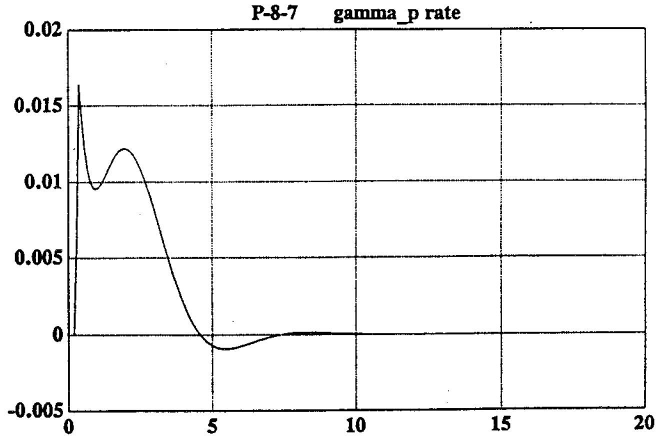

P-8-7 theta

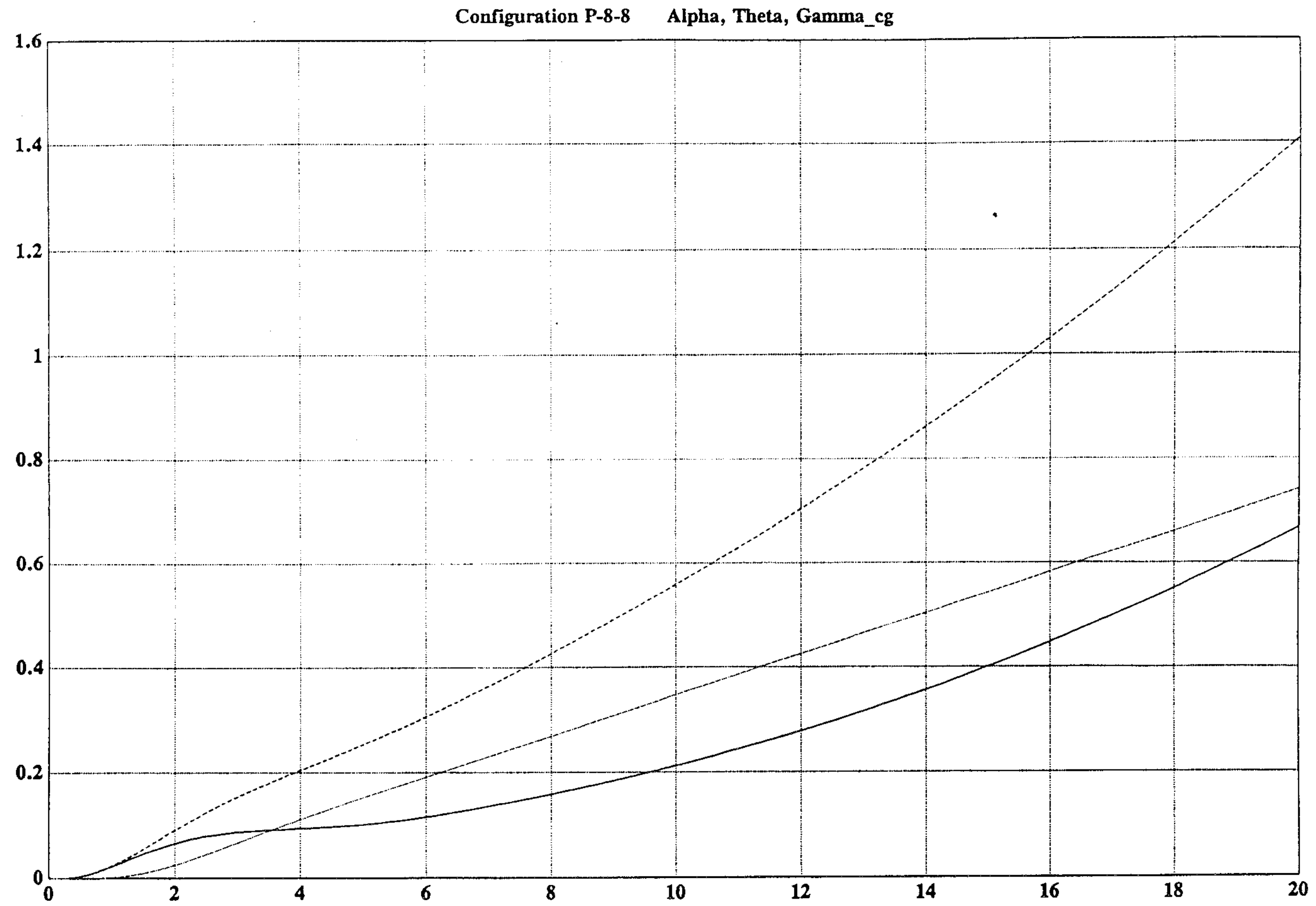

P-8-7 theta rate

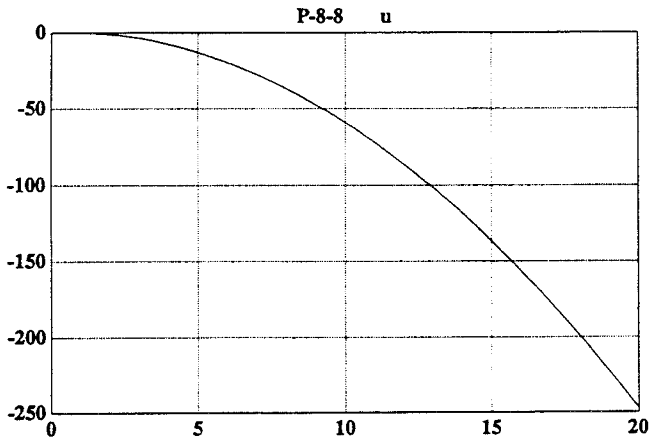

P-8-7 gamma_cg

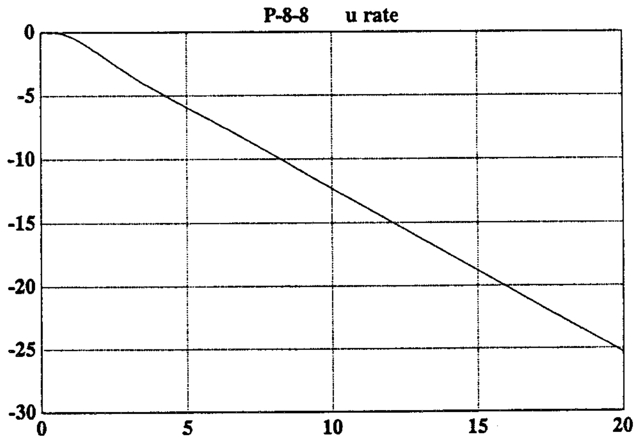

P-8-7 gamma_cg rate

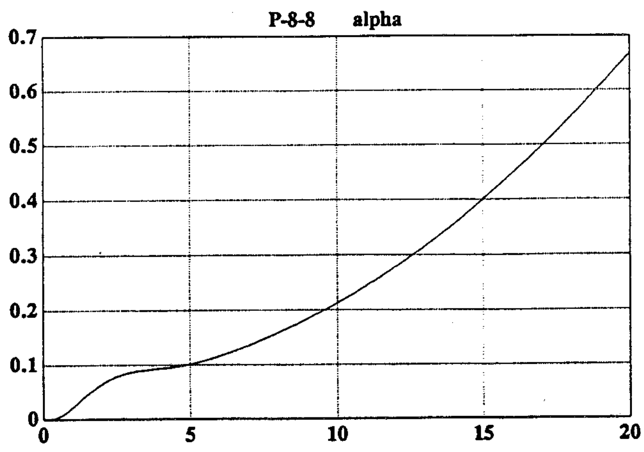

P-8-7 gamma_p

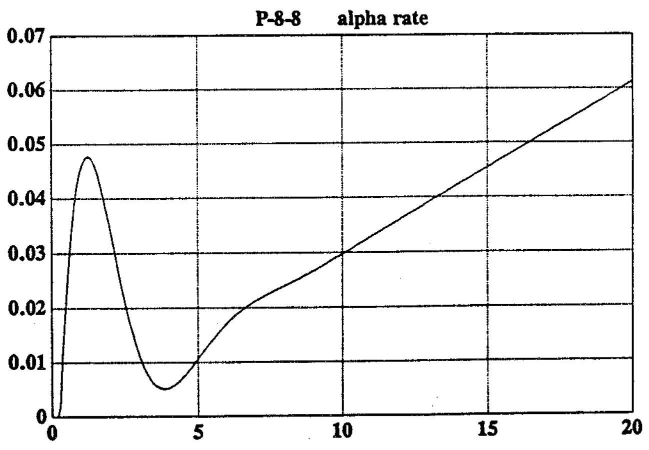

P-8-7 gamma_p rate

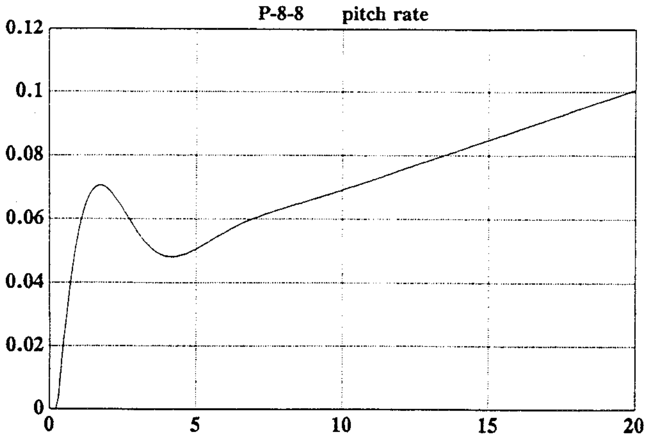

Configuration P-8-8 Alpha, Theta, Gamma_cg
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

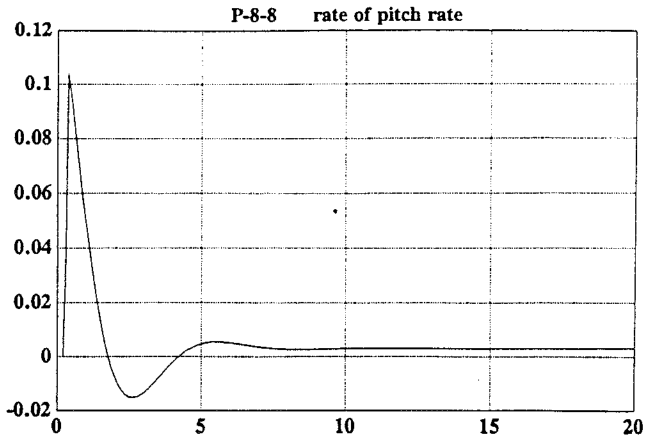

P-8-8 u
0
-50
-100
-150
-200
-250
0
5
10
15
20

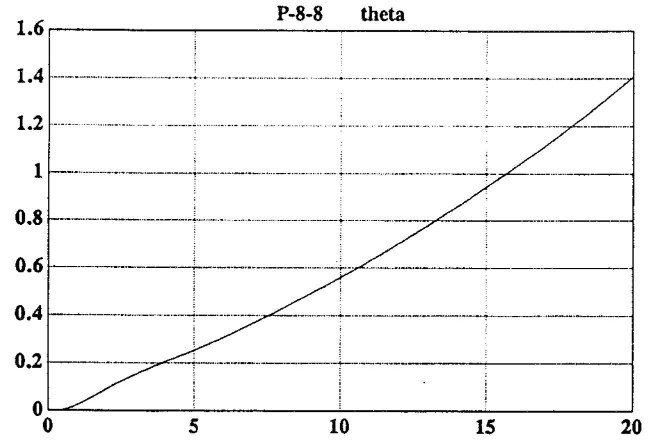

P-8-8 u rate
0
-5
-10
-15
-20
-25
-30
0
5
10
15
20

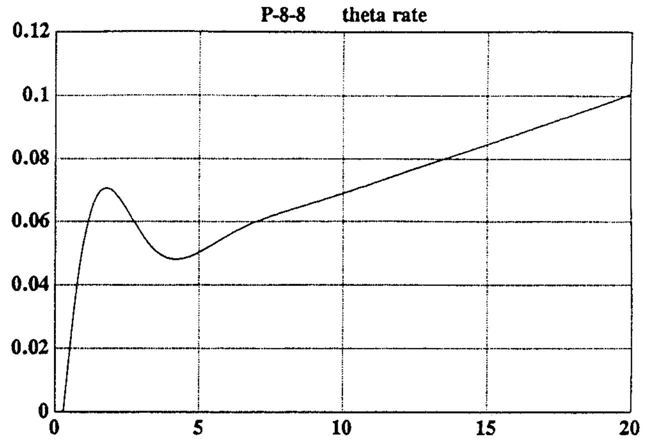

P-8-8 alpha
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

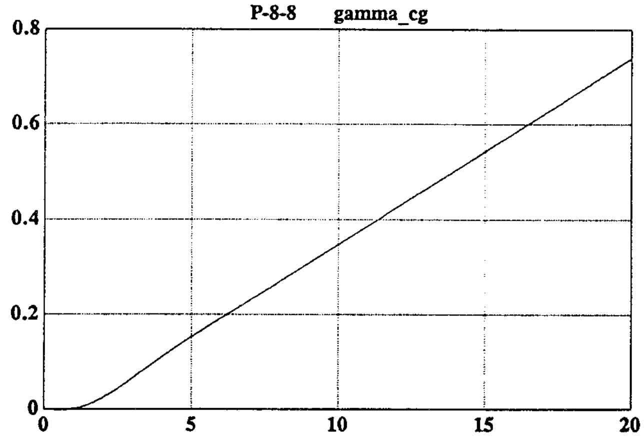

P-8-8 alpha rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

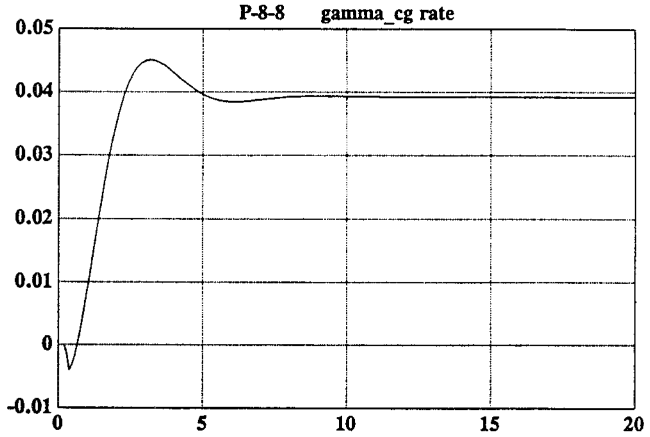

P-8-8 pitch rate

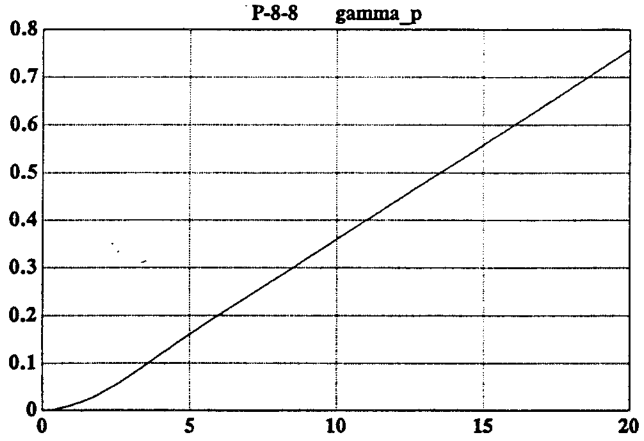

P-8-8 rate of pitch rate

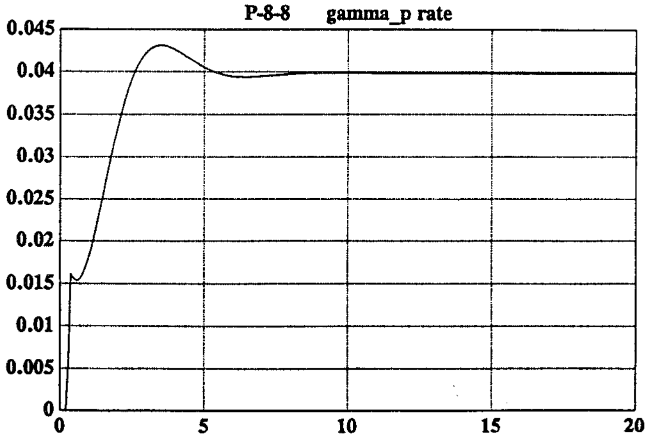

P-8-8 theta

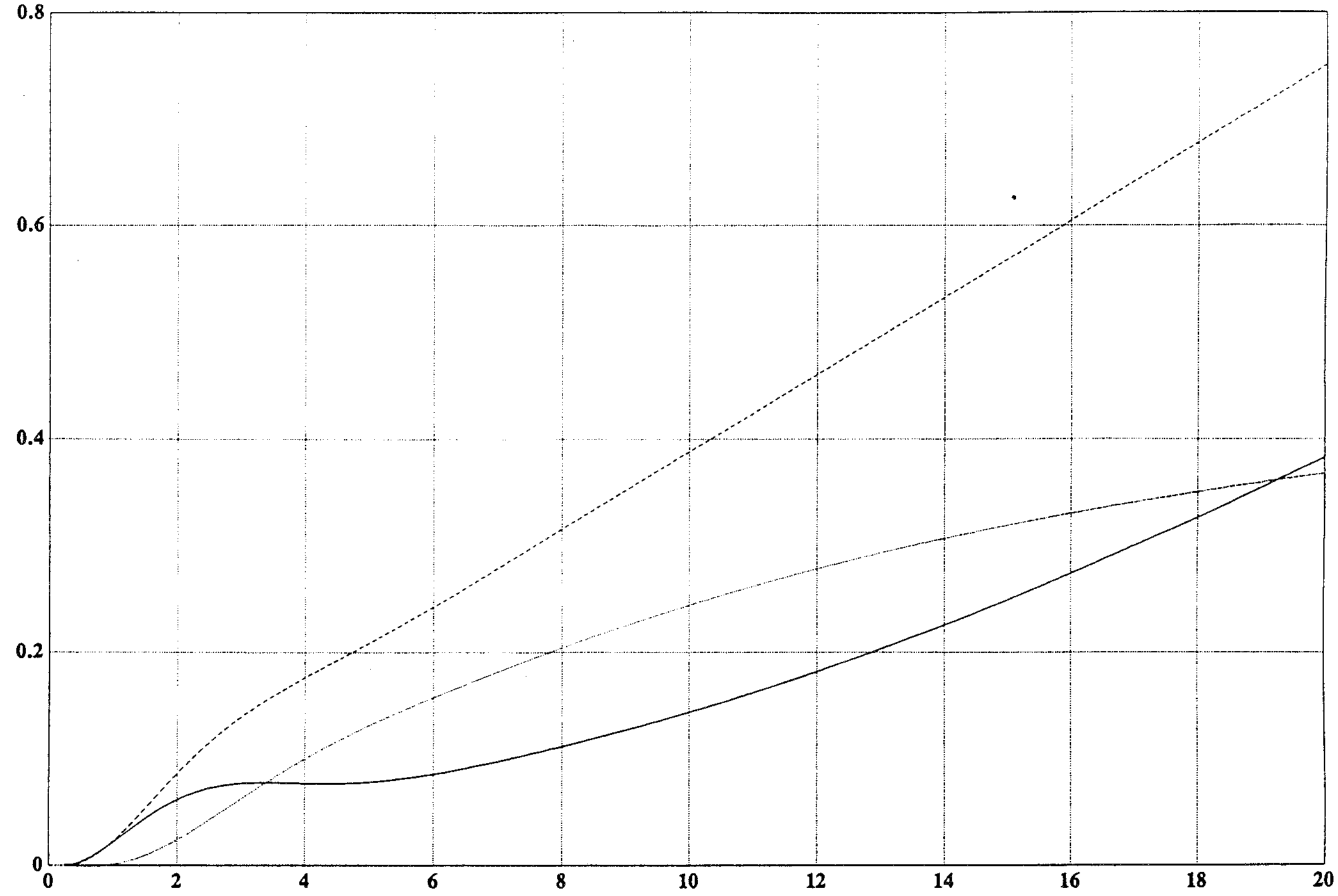

P-8-8 theta rate

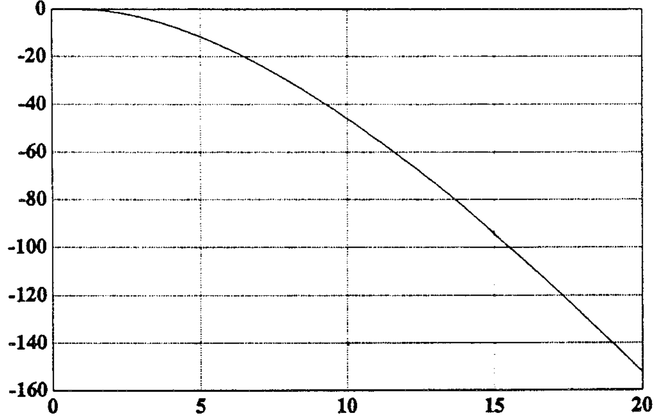

P-8-8 gamma_cg

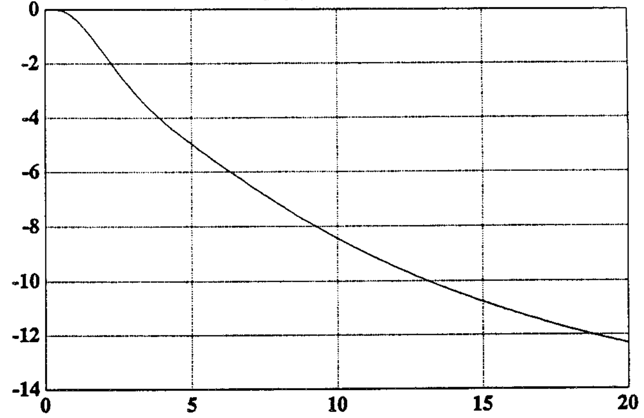

P-8-8 gamma_cg rate

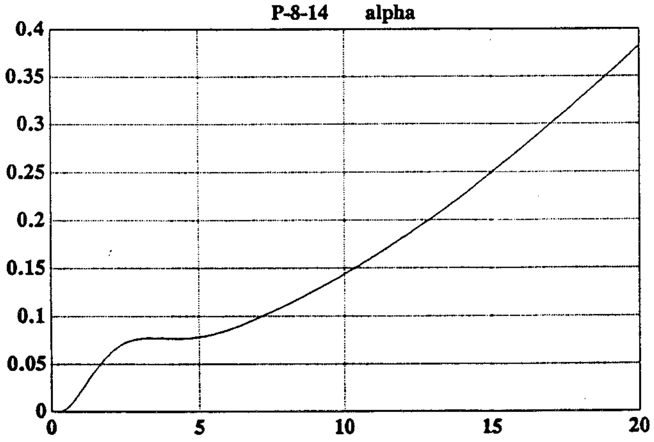

P-8-8 gamma_p

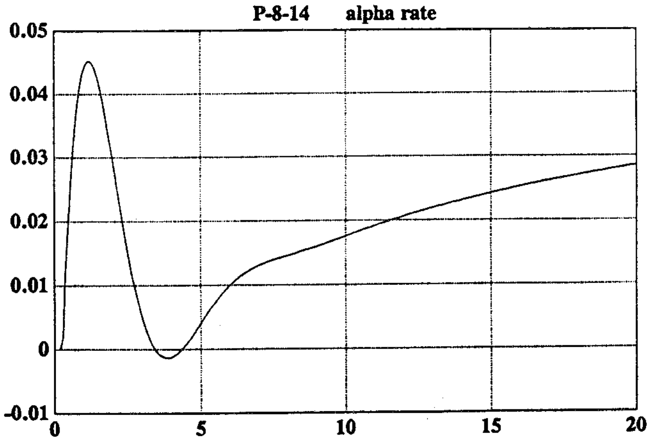

P-8-8 gamma_p rate

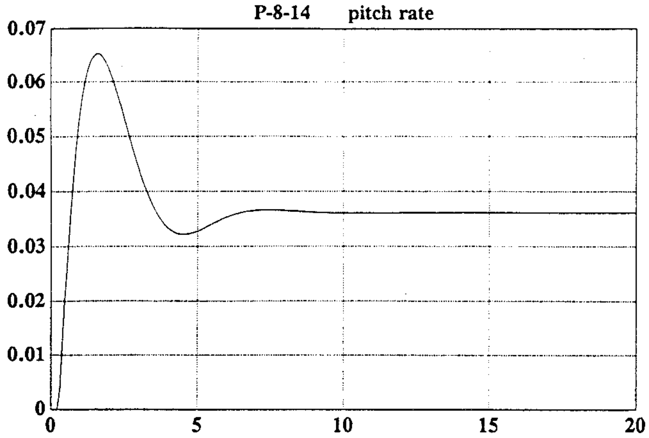

Configuration P-8-14 Alpha, Theta, Gamma_cg

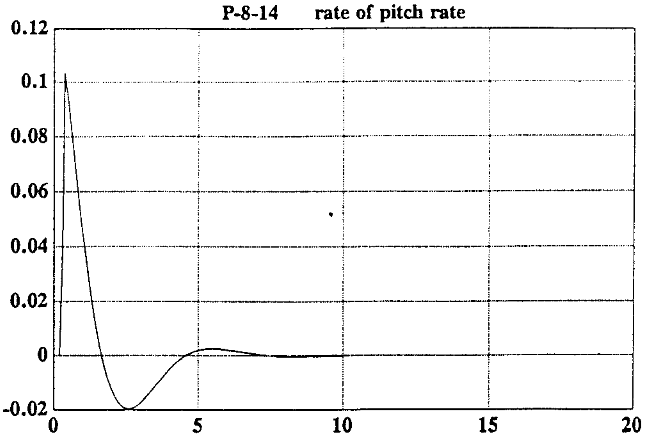

P-8-14 u

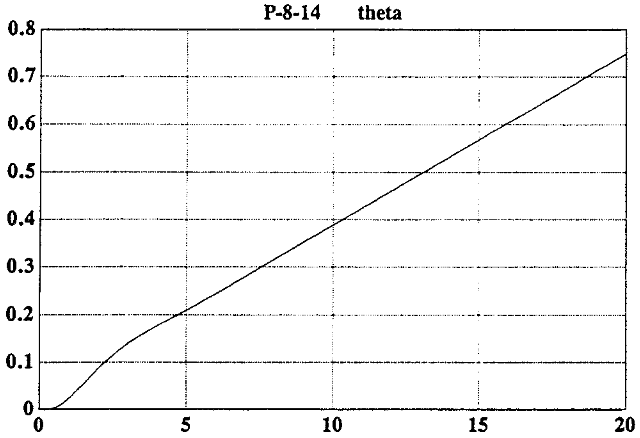

P-8-14 u rate

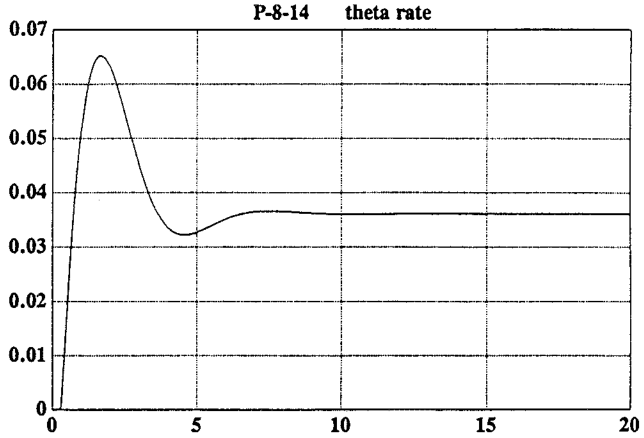

P-8-14 alpha

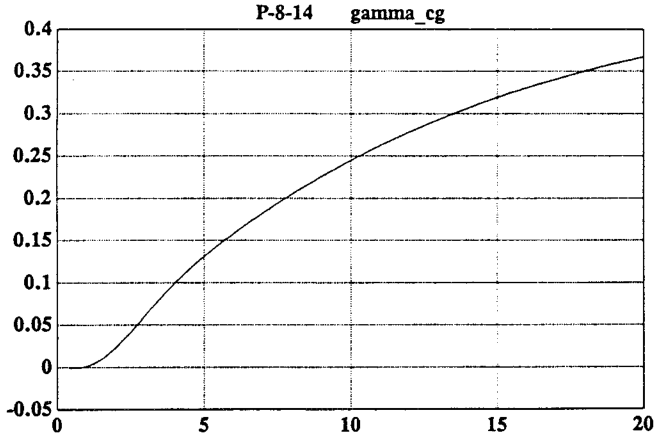

P-8-14 alpha rate

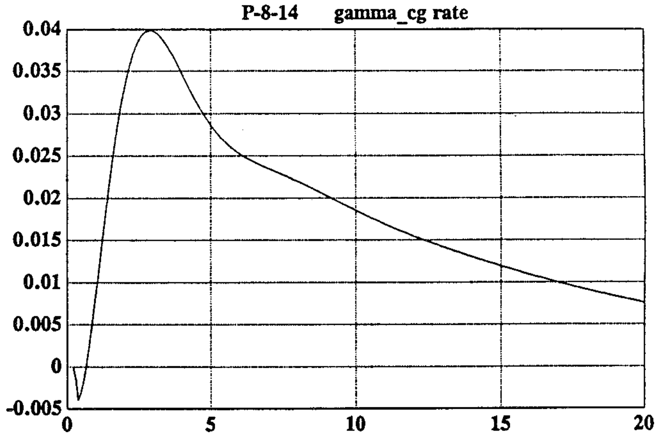

P-8-14 pitch rate

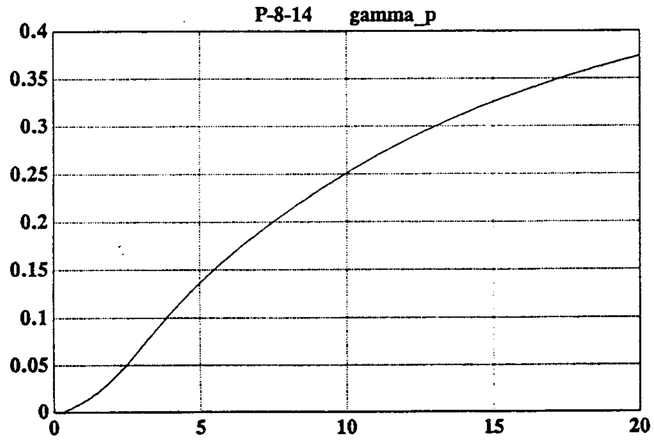

P-8-14 rate of pitch rate

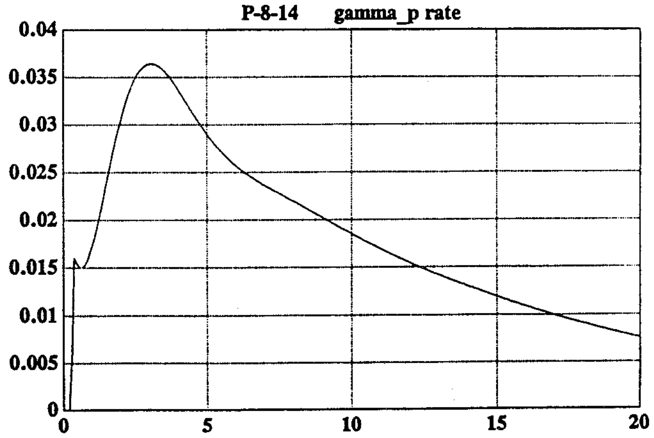

P-8-14 theta

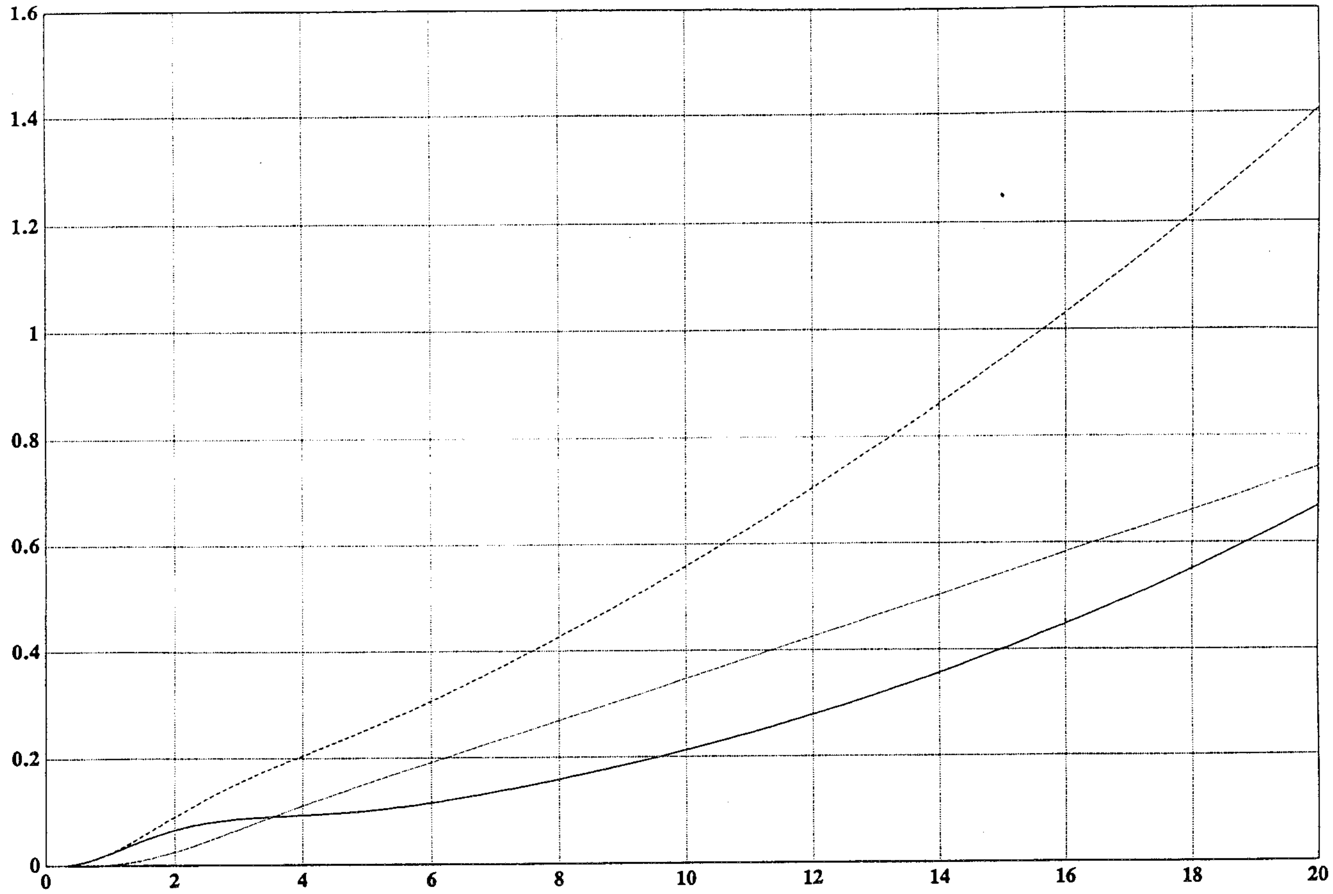

P-8-14 theta rate

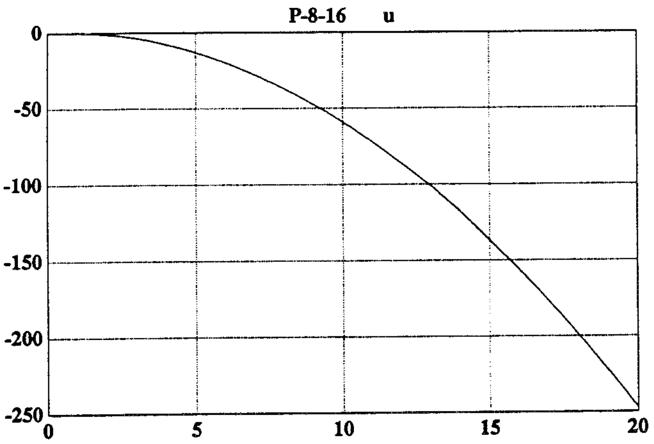

P-8-14 gamma_cg

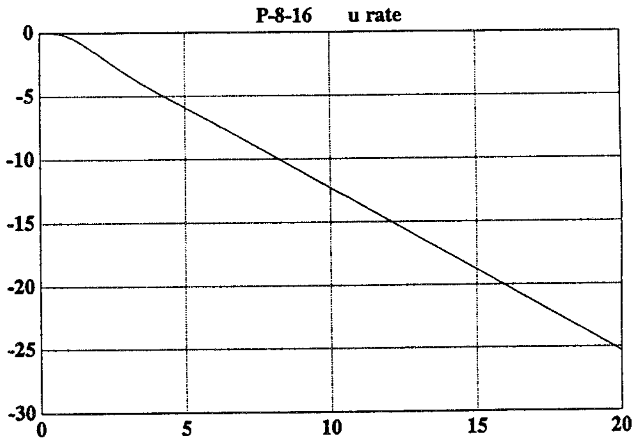

P-8-14 gamma_cg rate

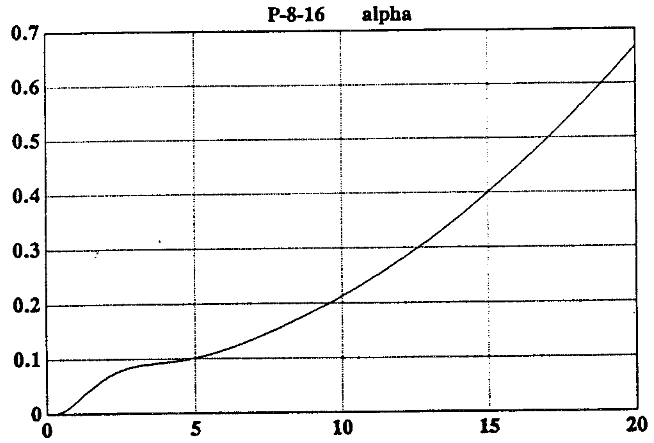

P-8-14 gamma_p

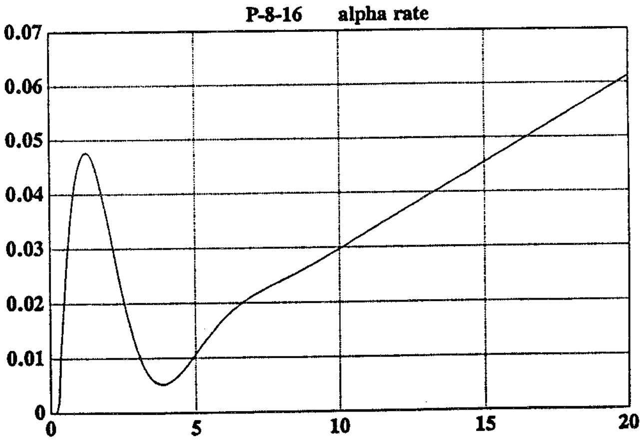

P-8-14 gamma_p rate

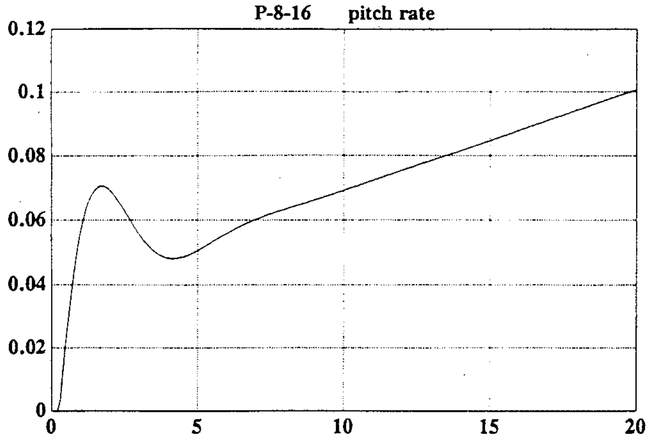

Configuration P-8-16 Alpha, Theta, Gamma_cg

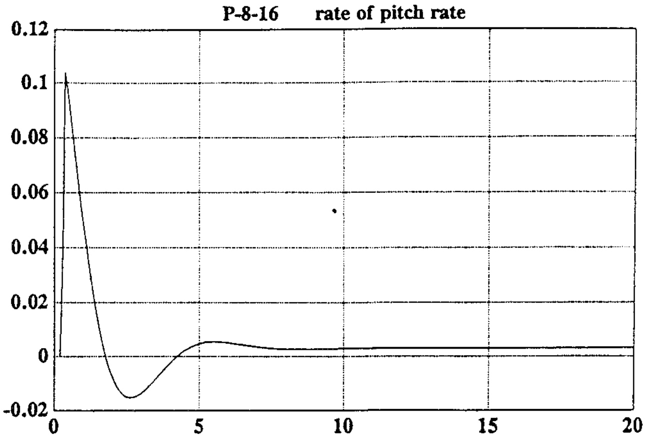

P-8-16 u

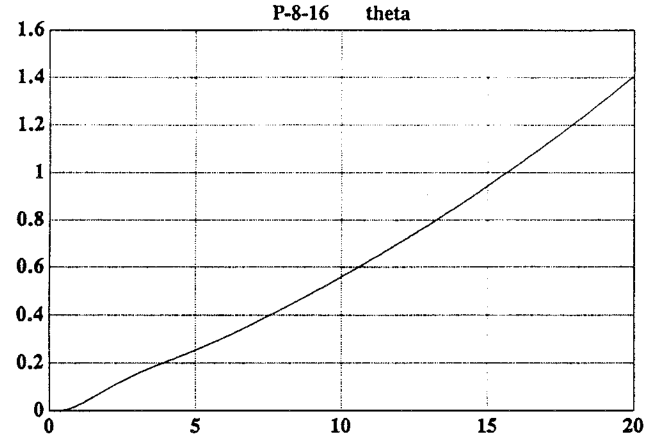

P-8-16 u rate

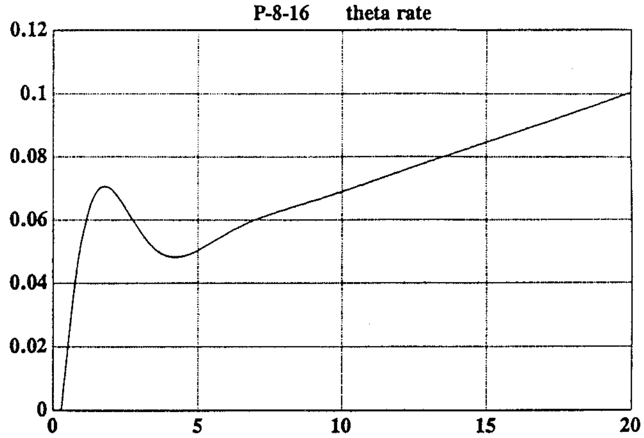

P-8-16 alpha

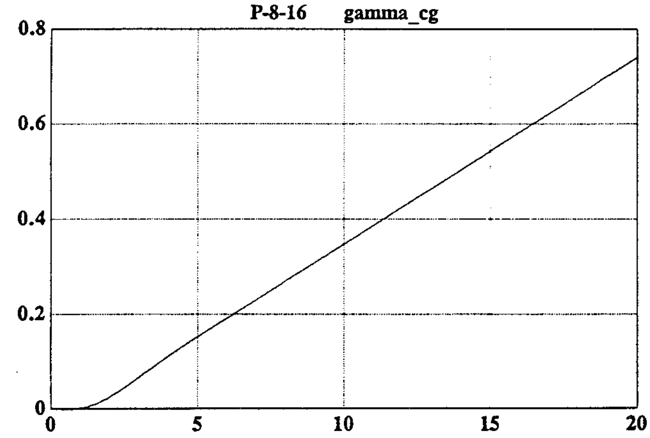

P-8-16 alpha rate

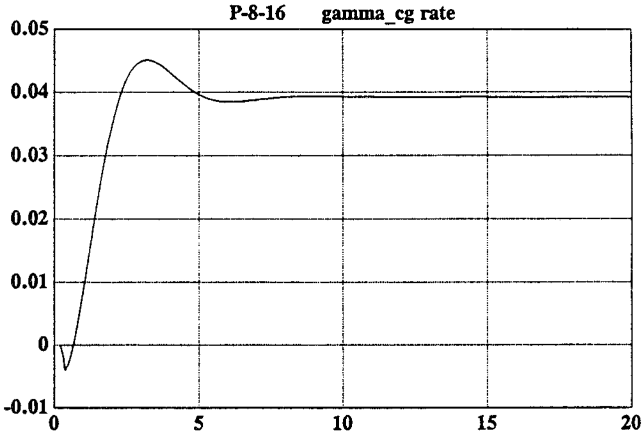

P-8-16 pitch rate

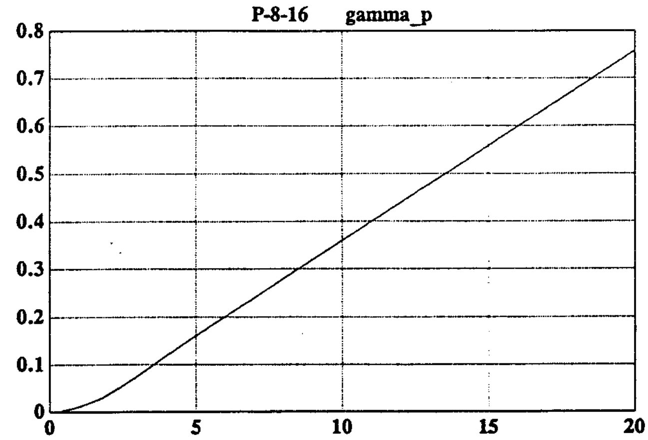

P-8-16 rate of pitch rate

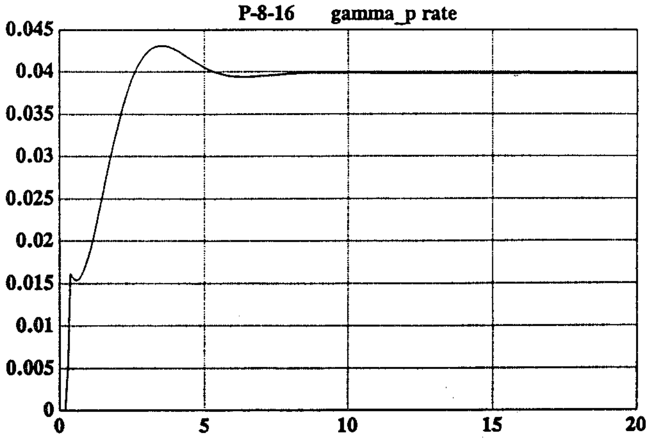

P-8-16 theta

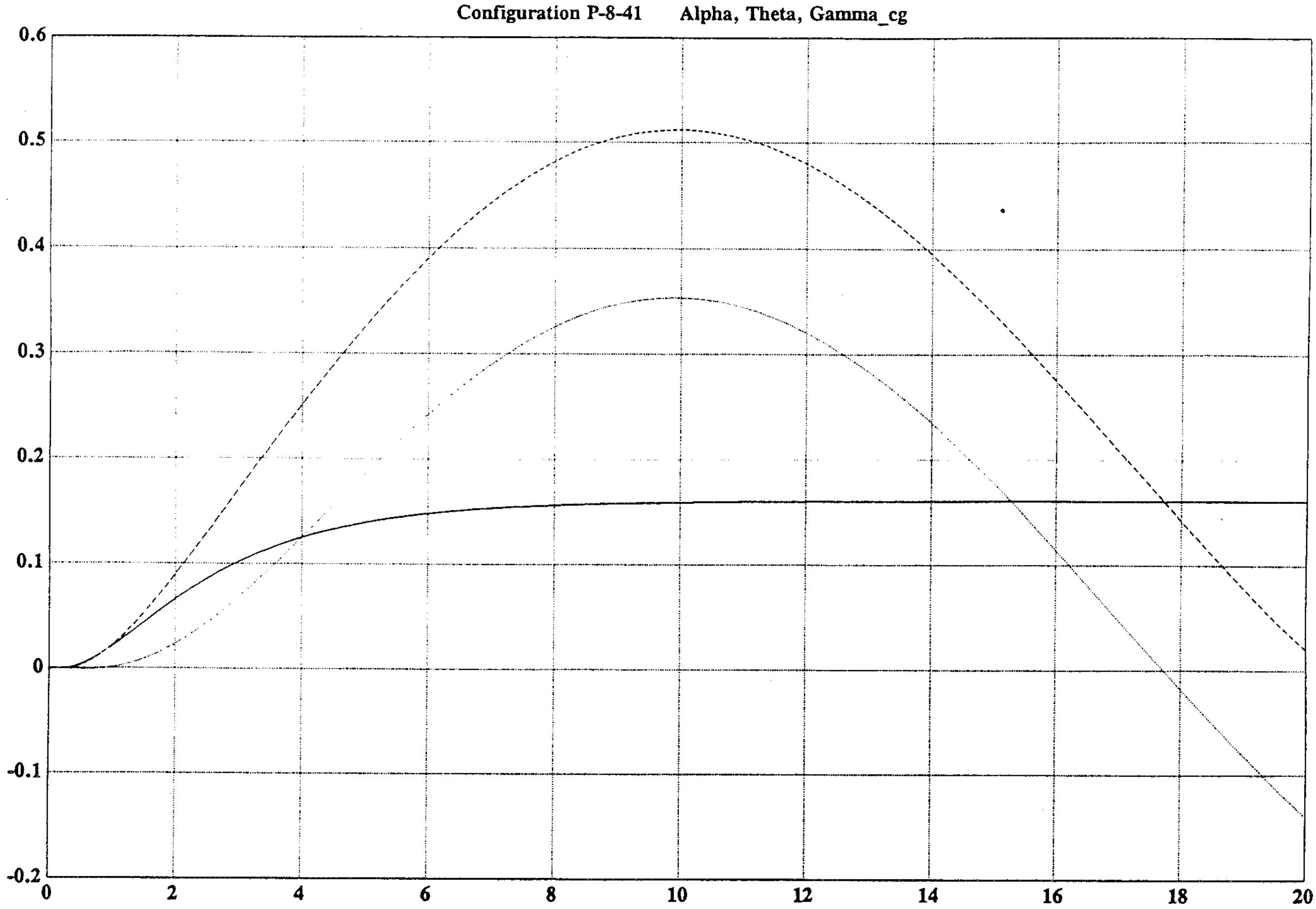

P-8-16 theta rate

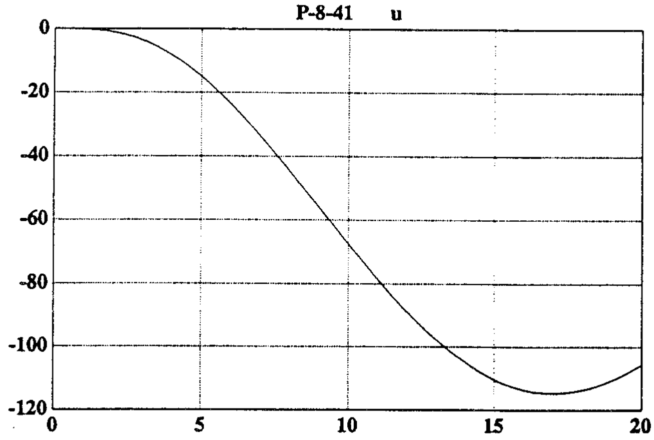

P-8-16 gamma_cg

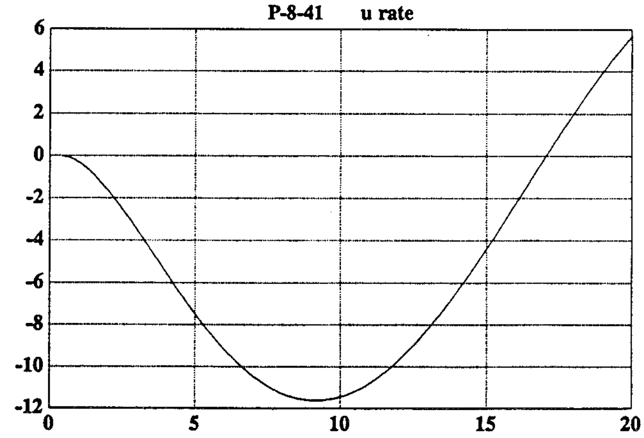

P-8-16 gamma_cg rate

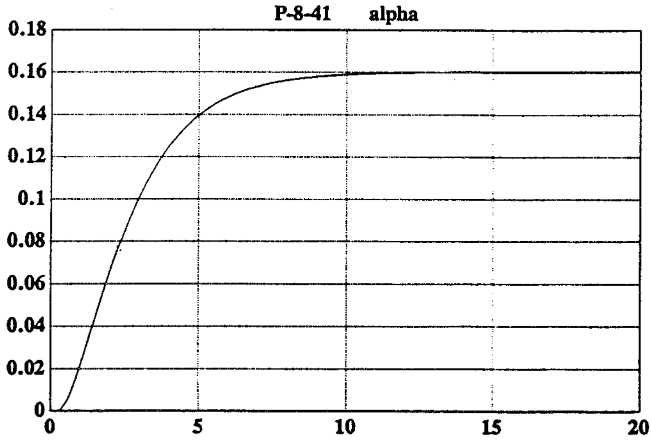

P-8-16 gamma_p

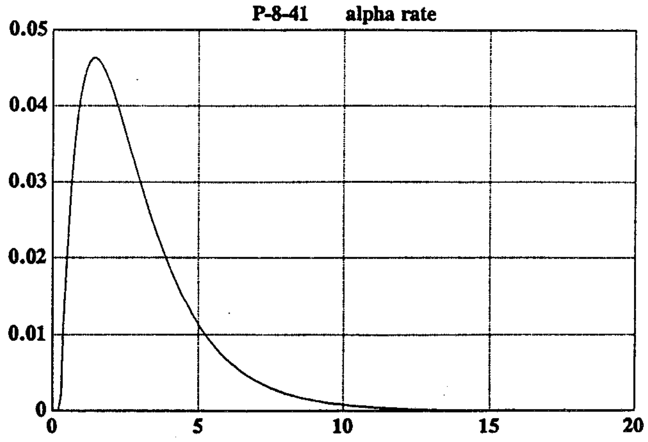

P-8-16 gamma_p rate

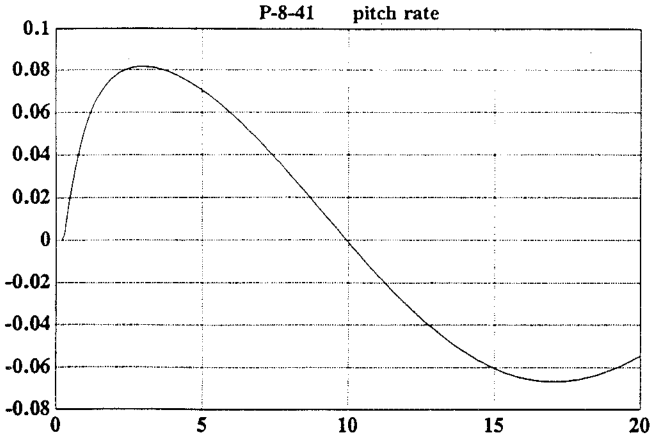

Configuration P-8-41 Alpha, Theta, Gamma_cg
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
2
4
6
8
10
12
14
16
18
20

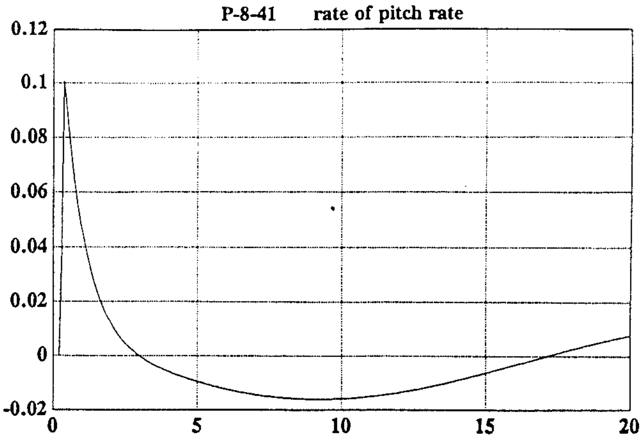

P-8-41 u
0
-20
-40
-60
-80
-100
-120
0
5
10
15
20

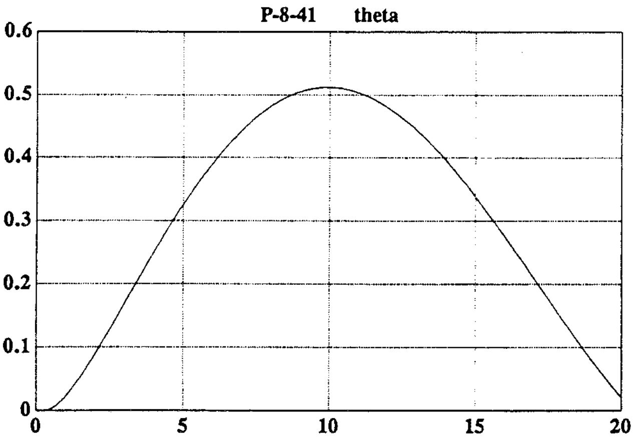

P-8-41 u rate
6
4
2
0
-2
-4
-6
-8
-10
-12
0
5
10
15
20

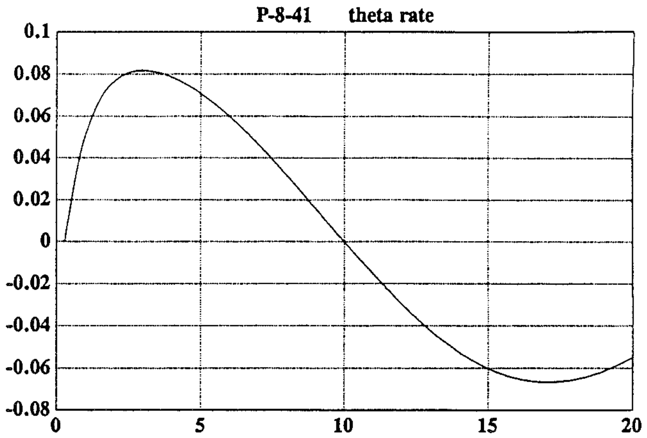

P-8-41 alpha
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

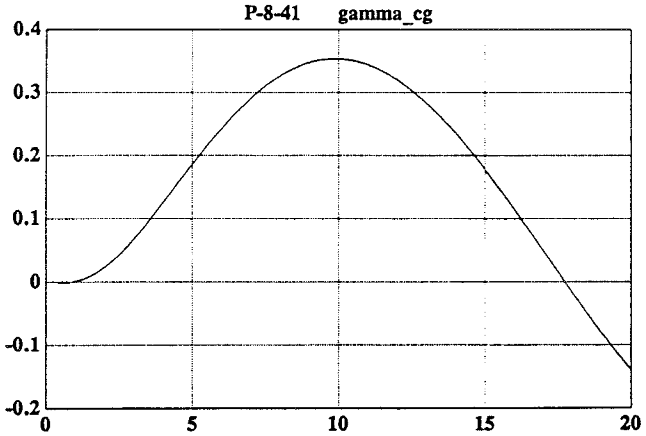

P-8-41 alpha rate
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

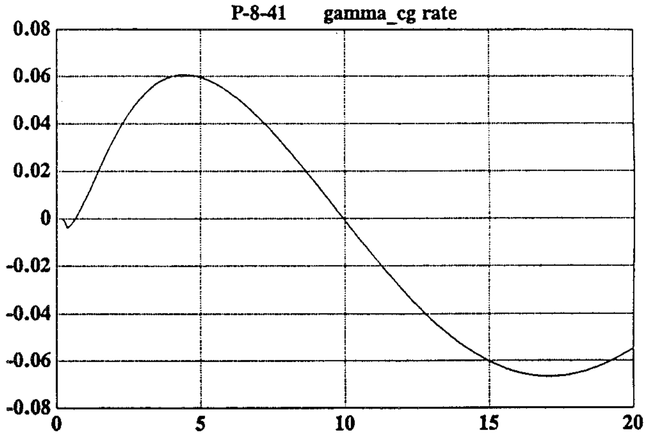

P-8-41 pitch rate

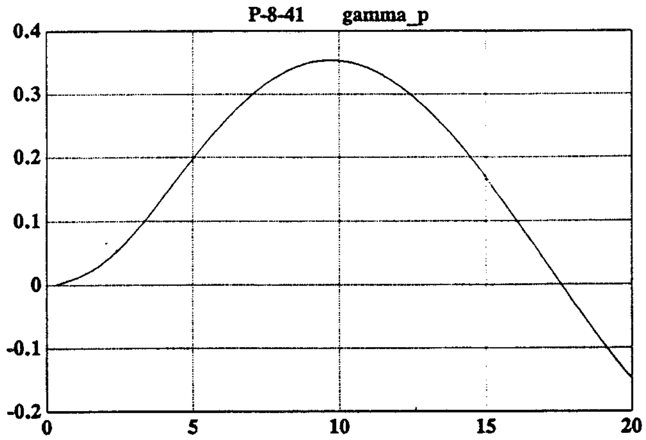

P-8-41 rate of pitch rate

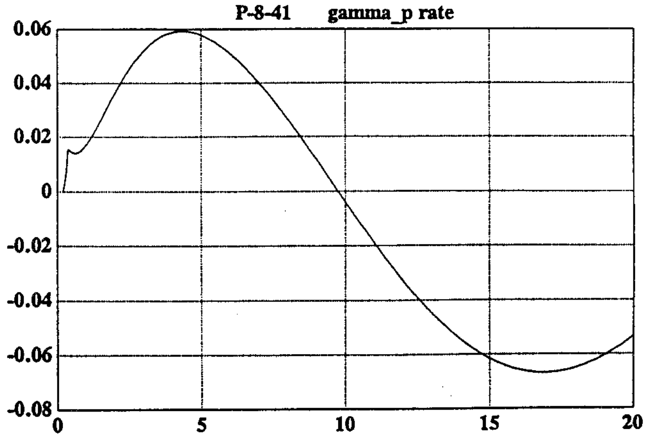

P-8-41 theta


P-8-41 theta rate

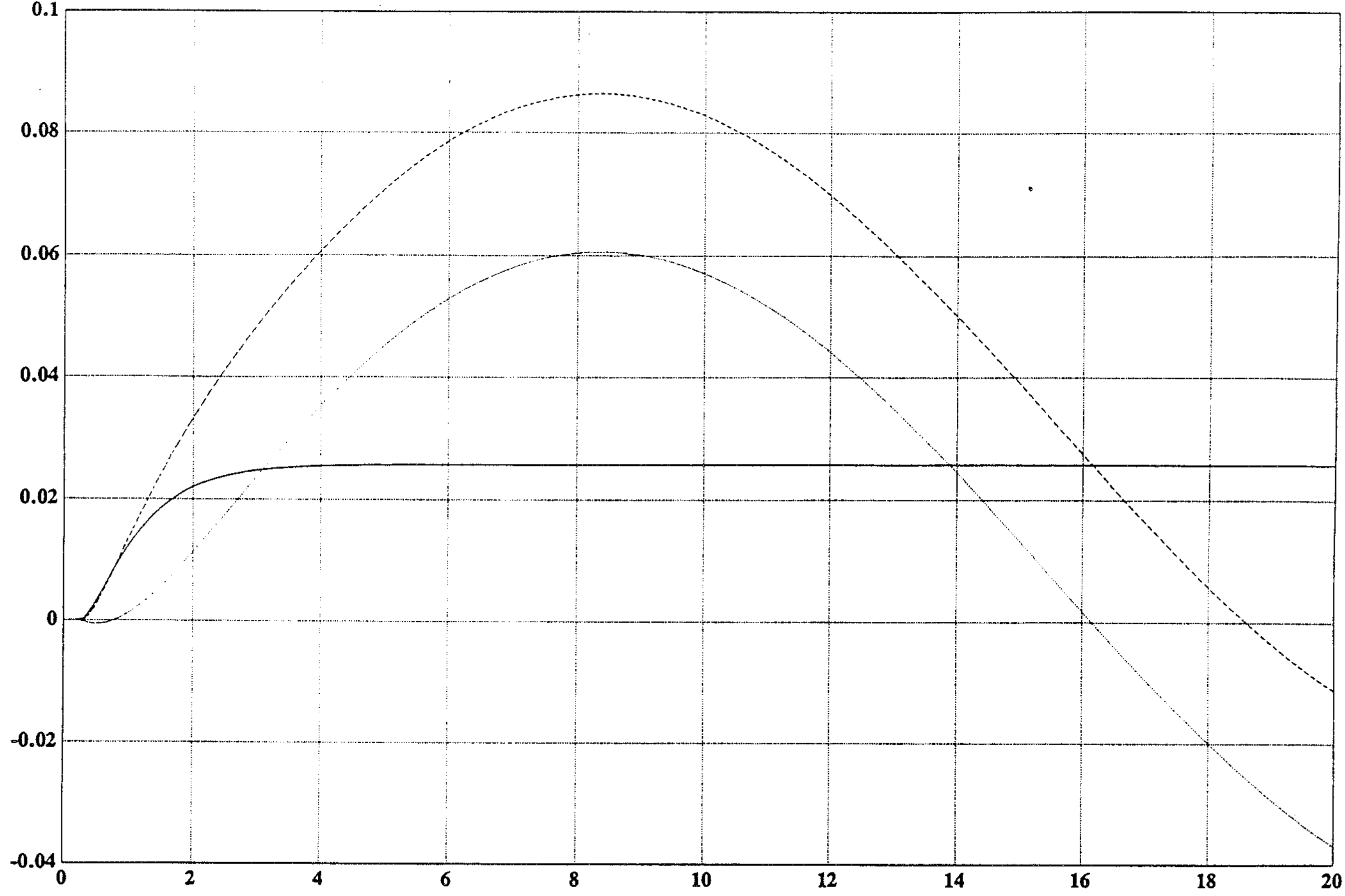

P-8-41 gamma_cg


P-8-41 gamma_cg rate

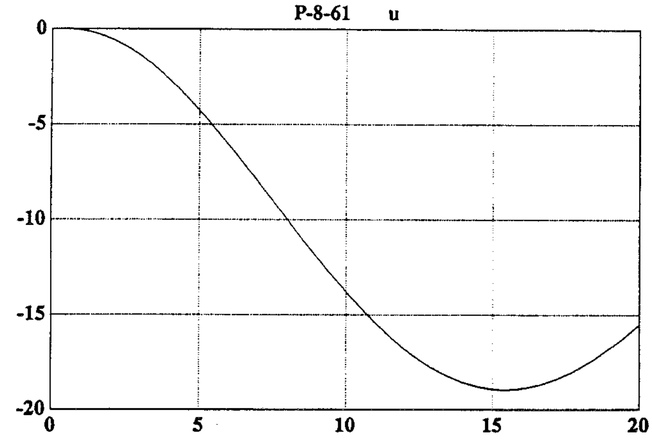

P-8-41 gamma_p


P-8-41 gamma_p rate

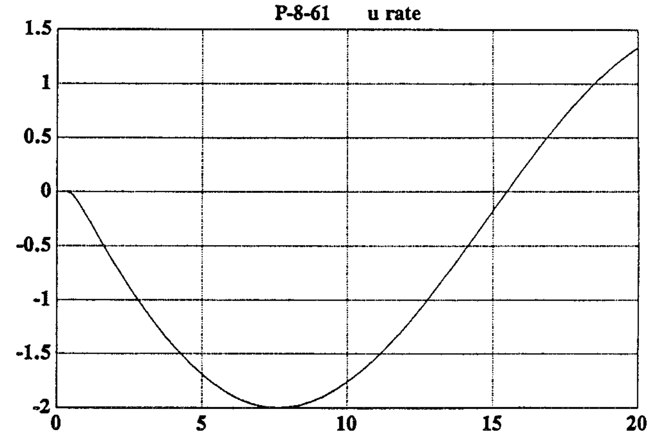
Configuration P-8-61 Alpha, Theta, Gamma_cg



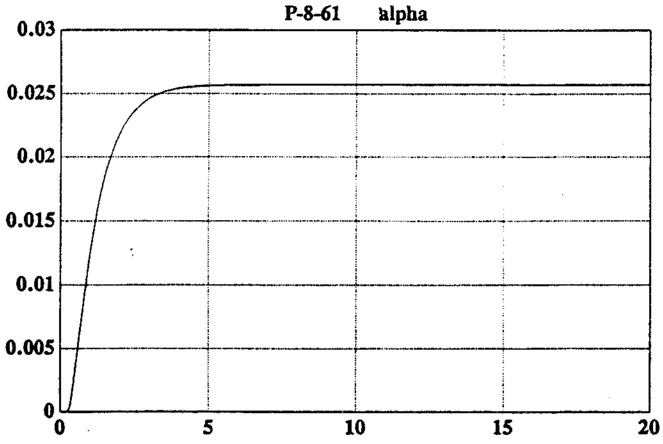
P-8-61 u



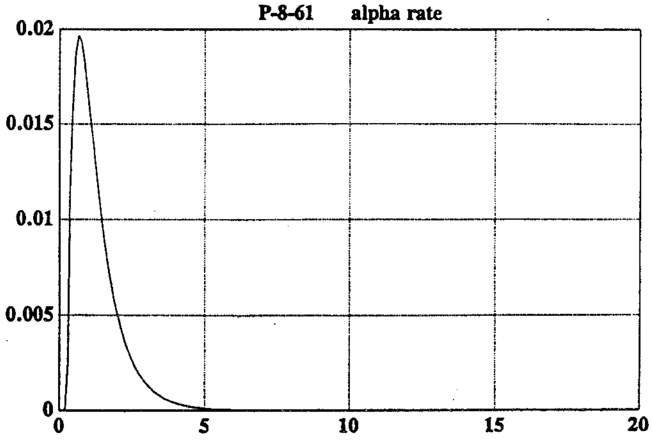
P-8-61 u rate

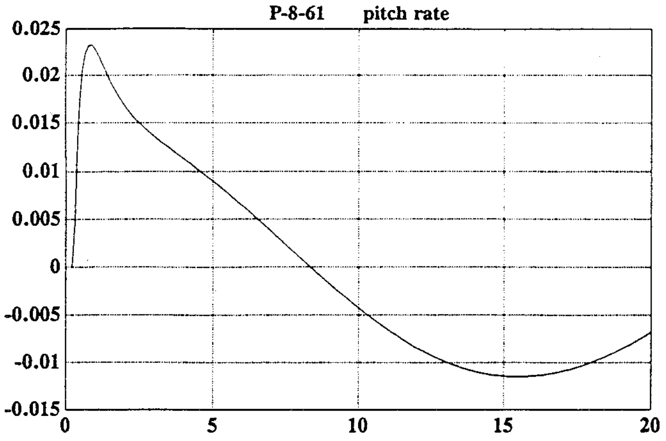


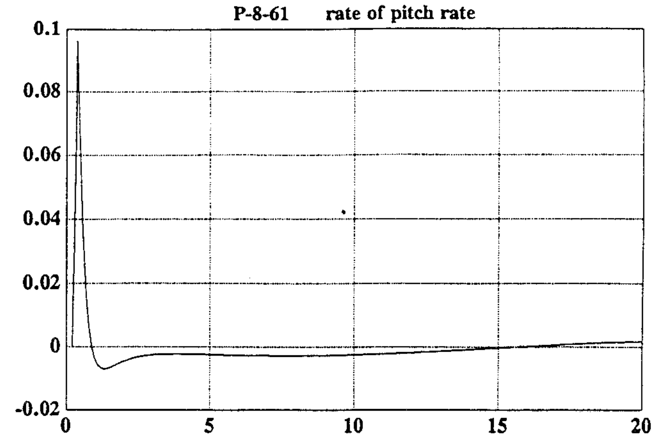
P-8-61 alpha

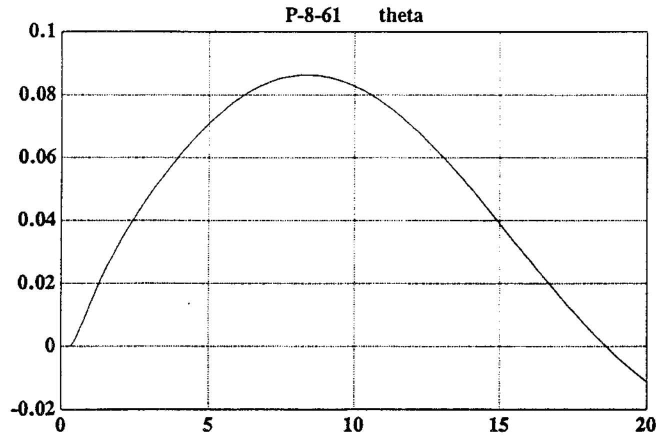


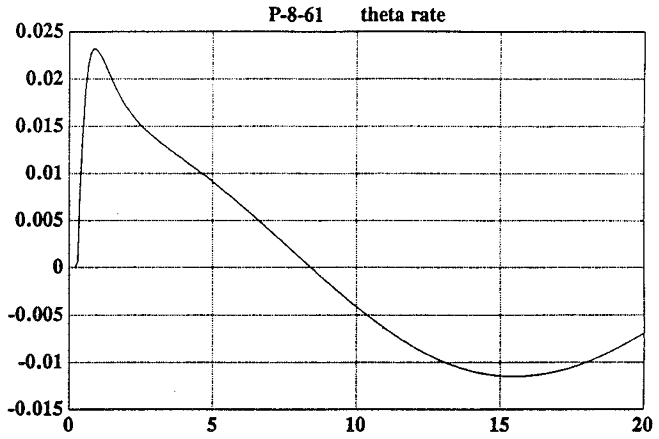
P-8-61 alpha rate

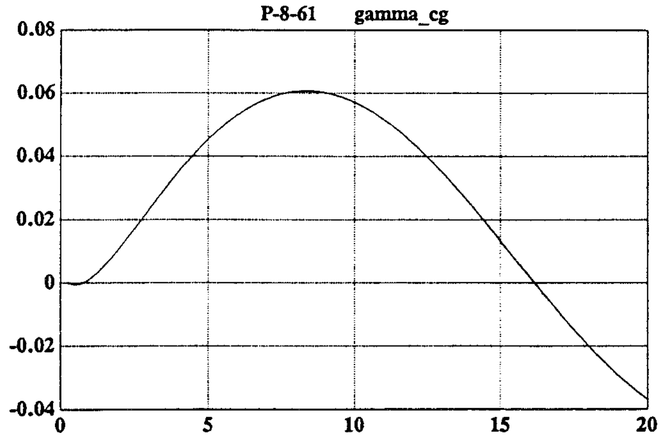



P-8-61 pitch rate
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0
5
10
15
20

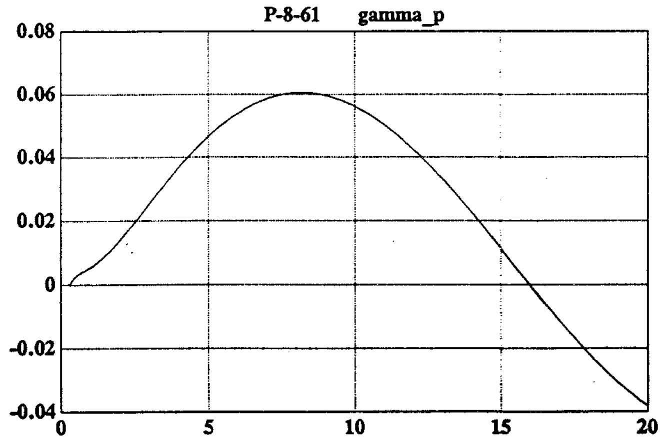

P-8-61 rate of pitch rate
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
5
10
15
20

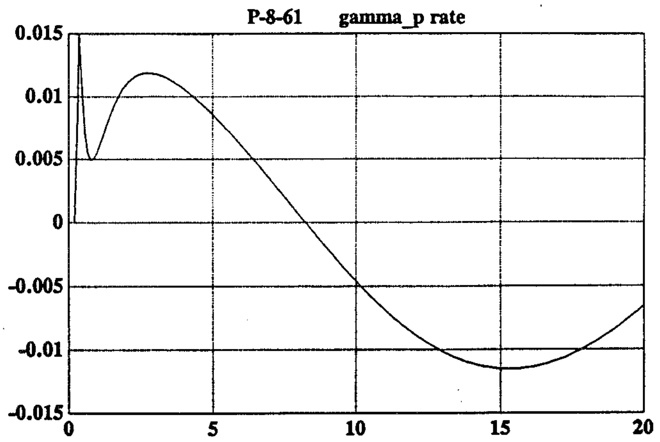

P-8-61 theta
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
5
10
15
20


P-8-61 theta rate
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0
5
10
15
20

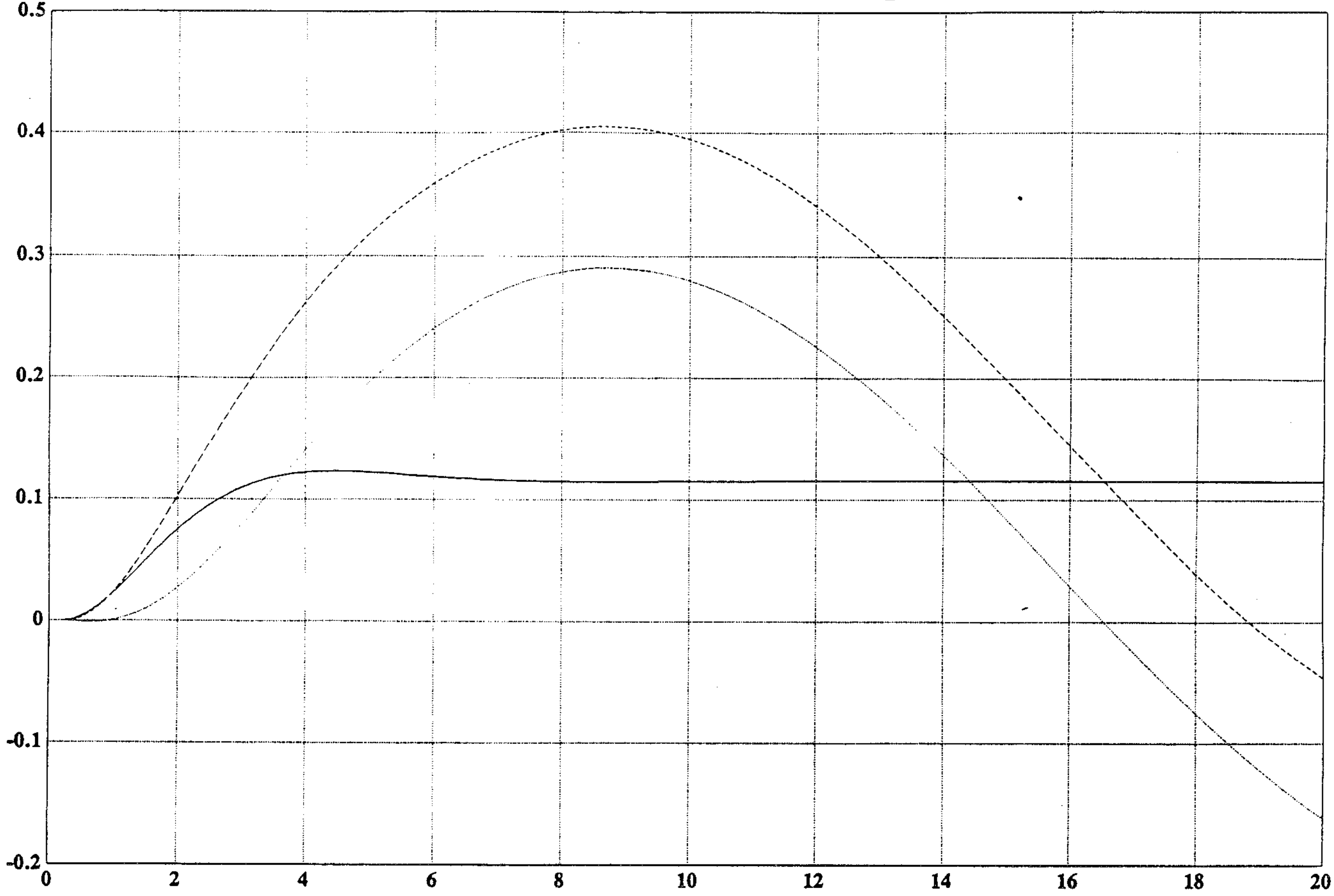

P-8-61 gamma_cg
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20


P-8-61 gamma_cg rate
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0
5
10
15
20

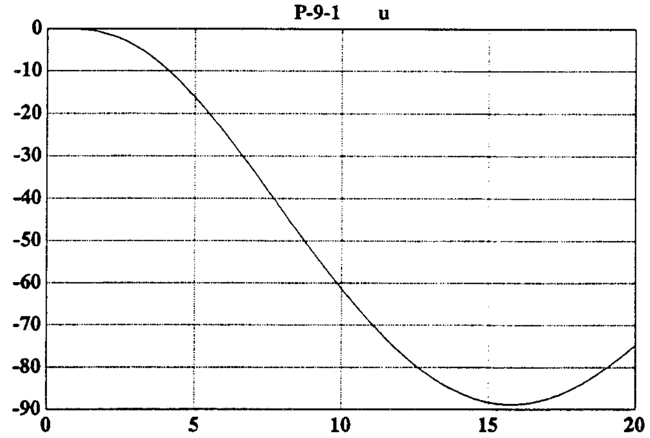

P-8-61 gamma_p
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20


P-8-61 gamma_p rate
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0
5
10
15
20

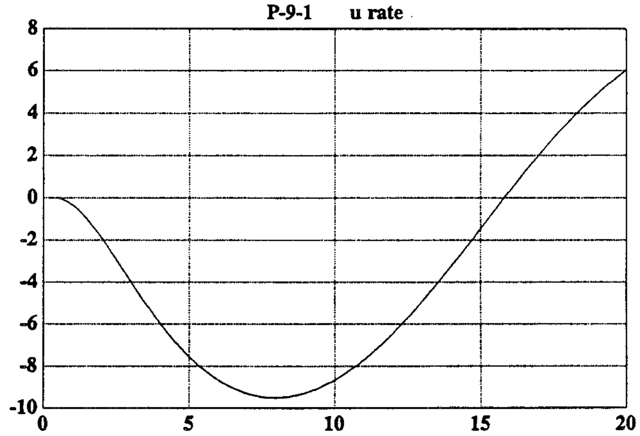
Configuration P-9-1 Alpha, Theta, Gamma_cg



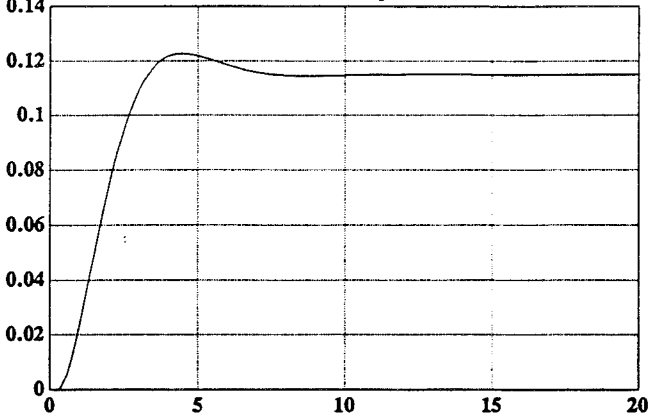
P-9-1 u



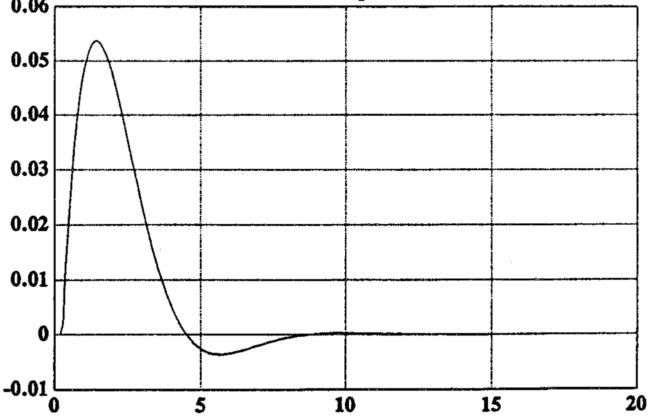
P-9-1 u rate

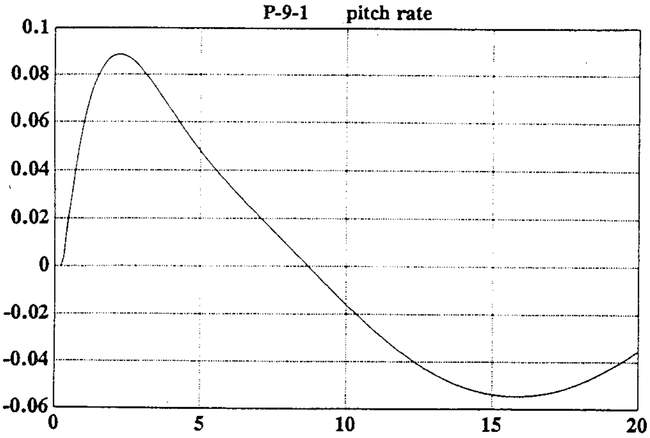


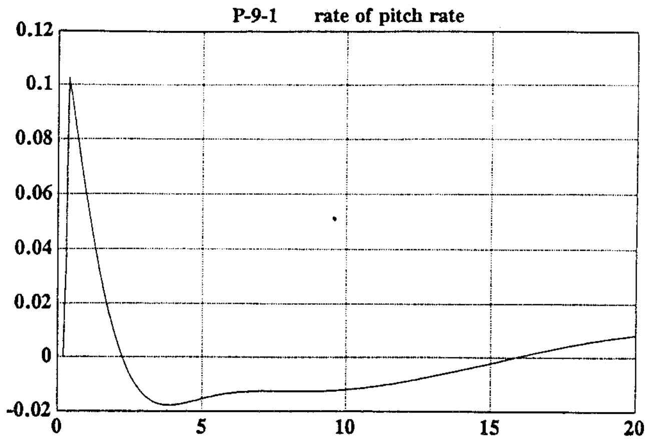
P-9-1 alpha

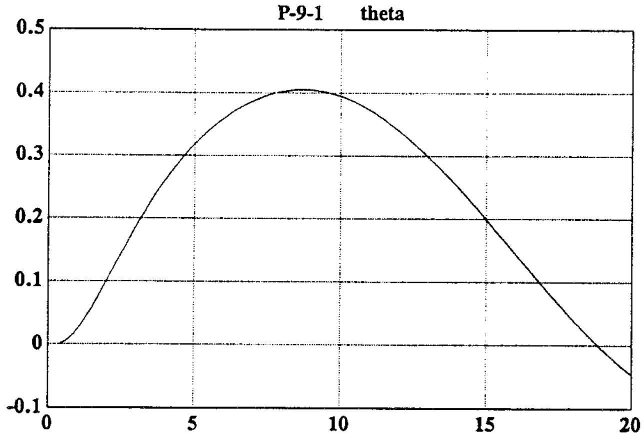


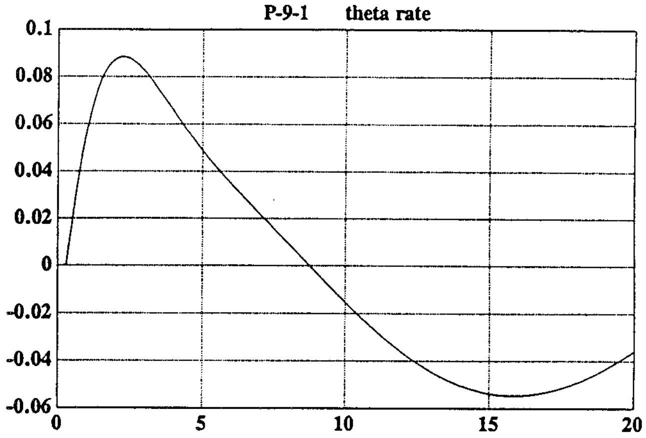
P-9-1 alpha rate

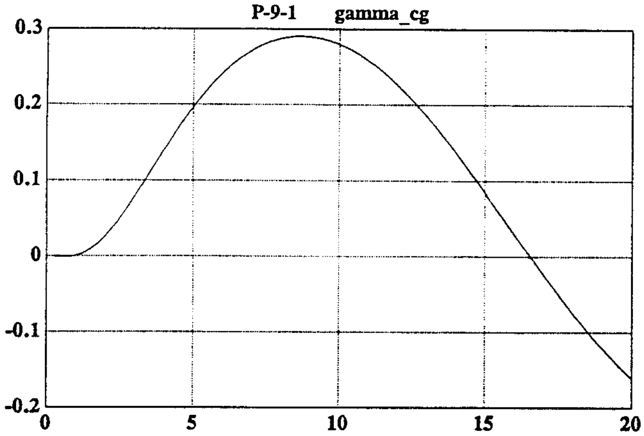


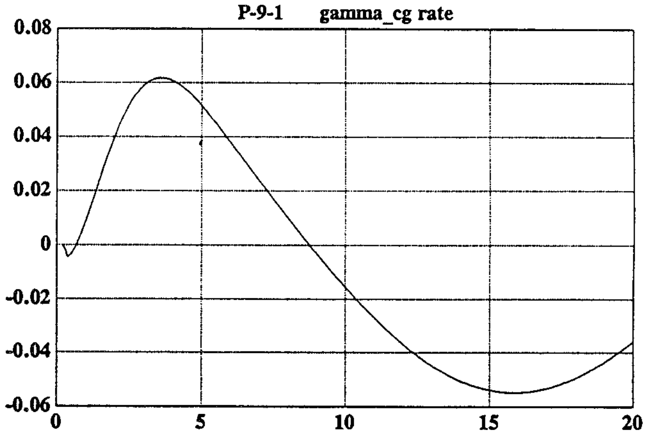

P-9-1 pitch rate
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
5
10
15
20

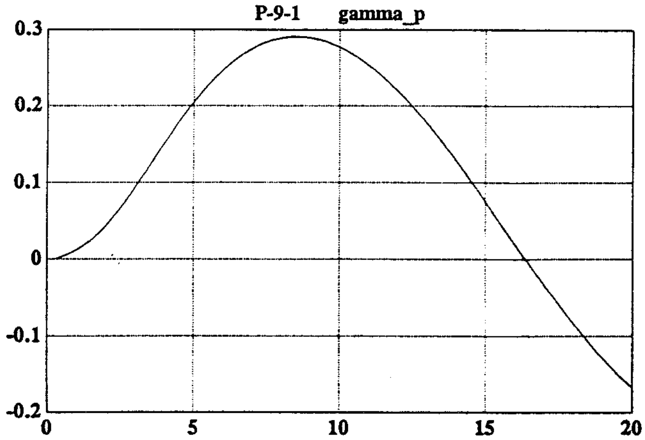

P-9-1 rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
5
10
15
20

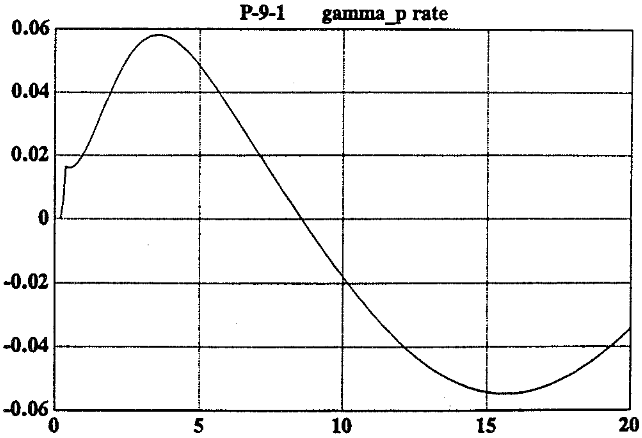

P-9-1 theta
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20

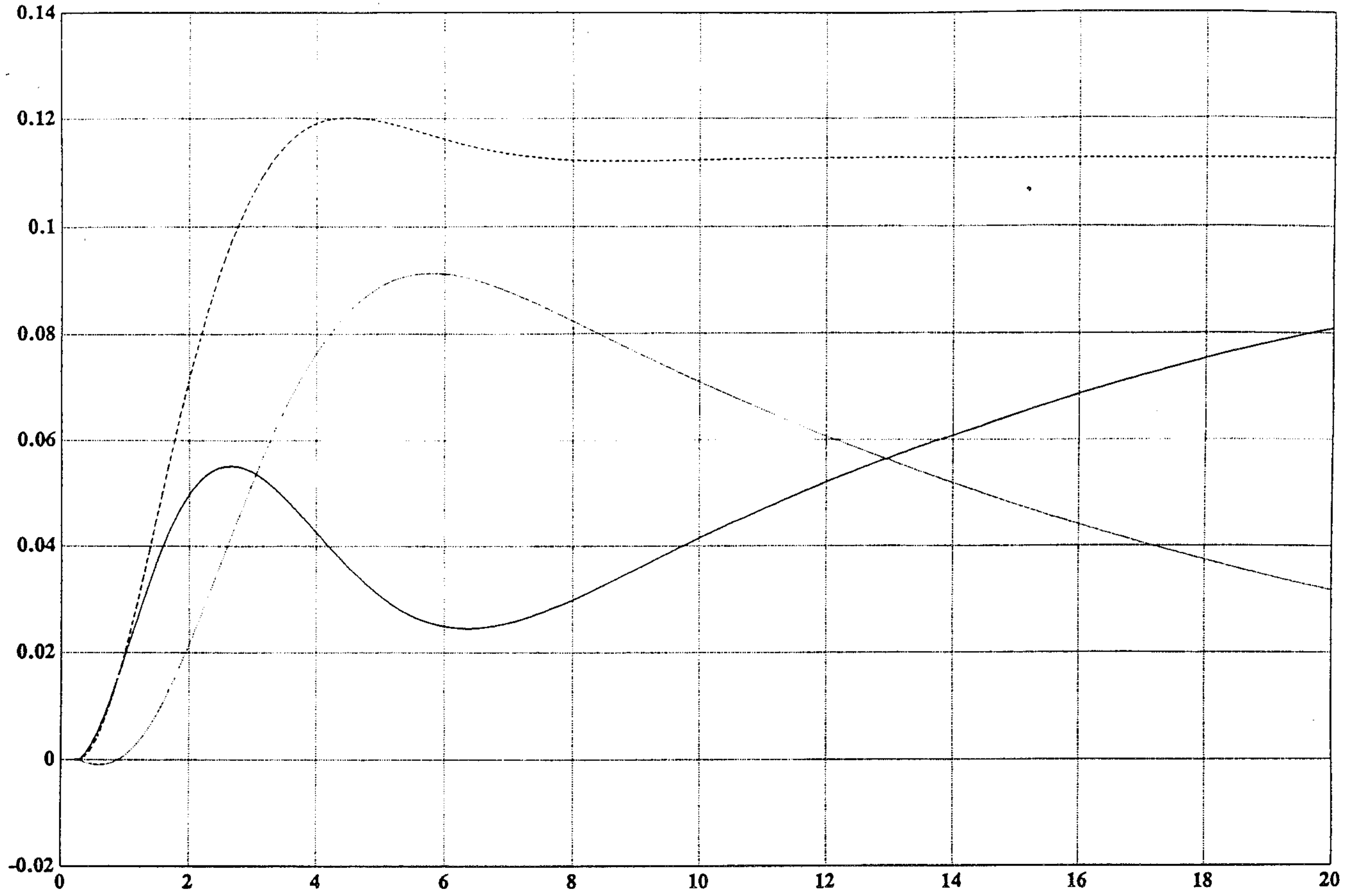

P-9-1 theta rate
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
5
10
15
20

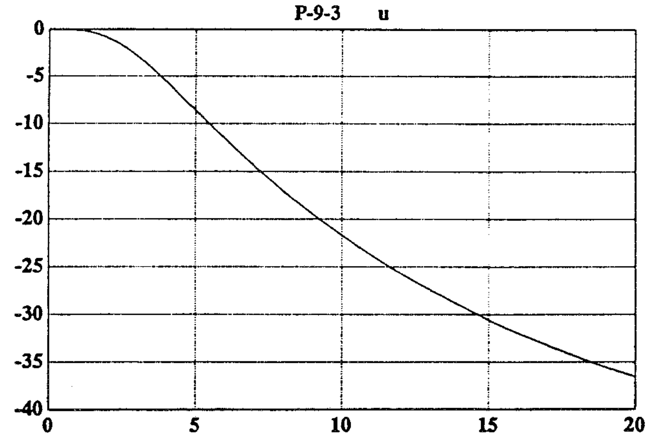

P-9-1 gamma_cg
0.3
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20

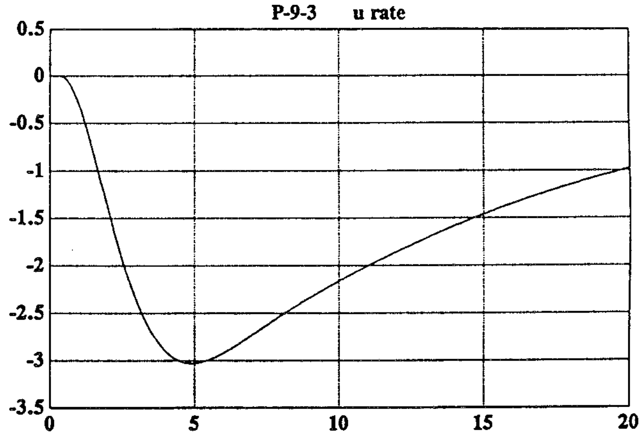

P-9-1 gamma_cg rate
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
5
10
15
20

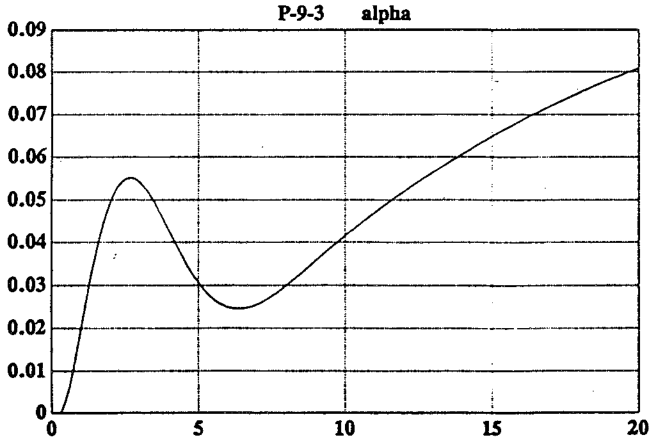

P-9-1 gamma_p
0.3
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20

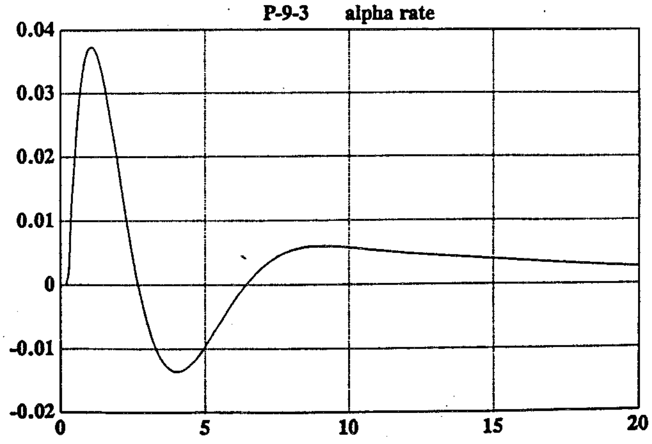

P-9-1 gamma_p rate
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
5
10
15
20

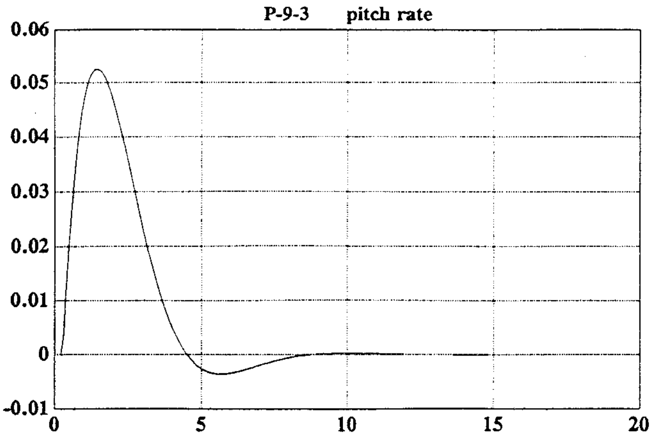

Configuration P-9-3 Alpha, Theta, Gamma_cg

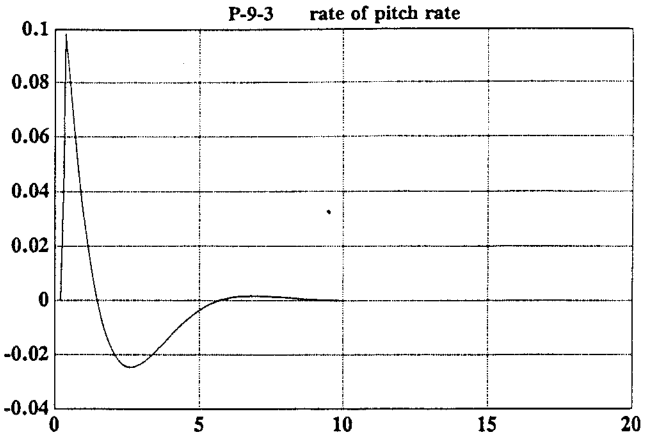

P-9-3 u

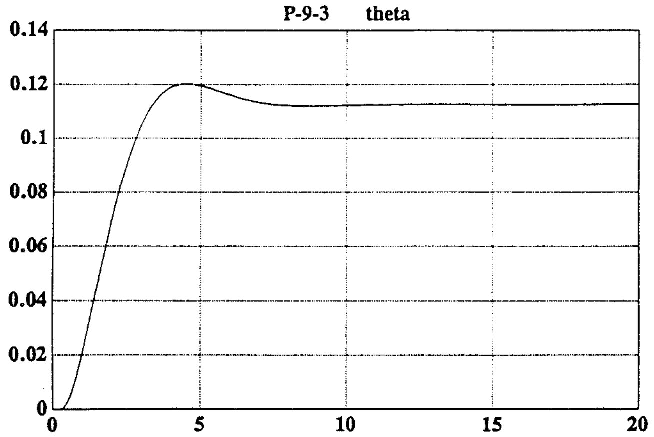

P-9-3 u rate

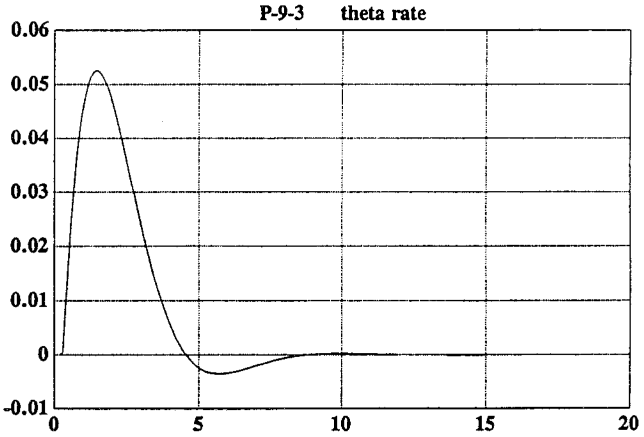

P-9-3 alpha

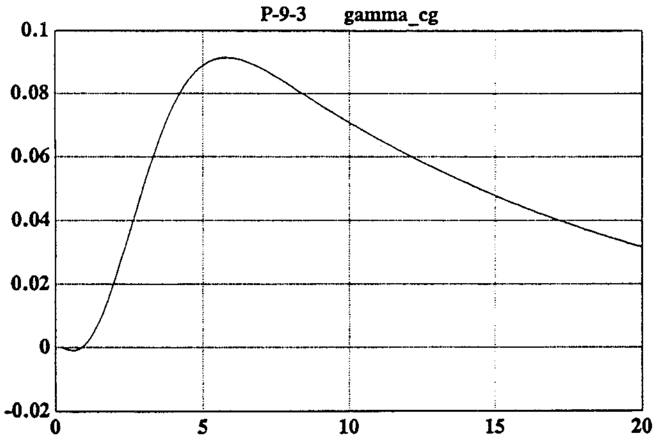

P-9-3 alpha rate

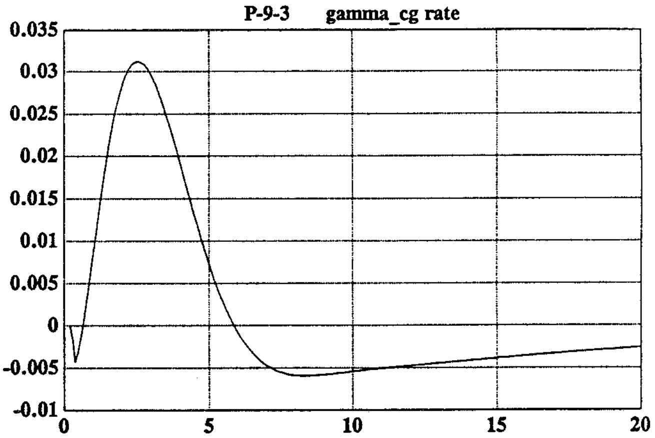

P-9-3 pitch rate

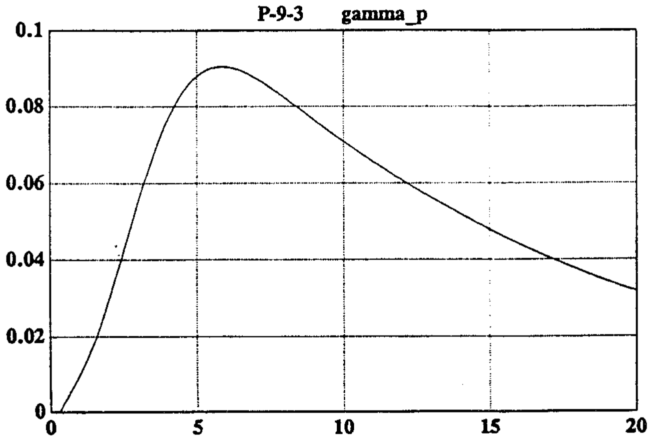

P-9-3 rate of pitch rate

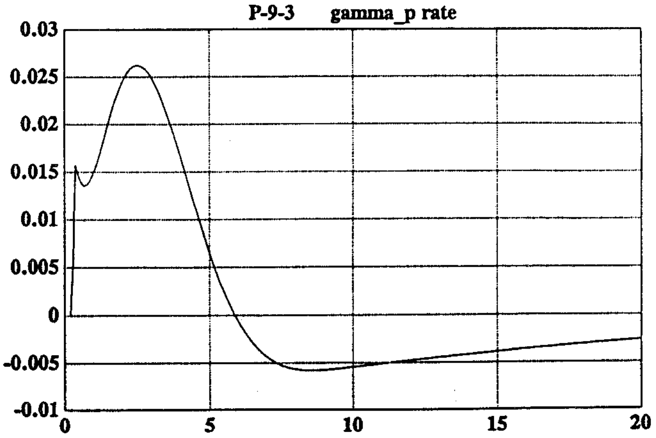

P-9-3 theta

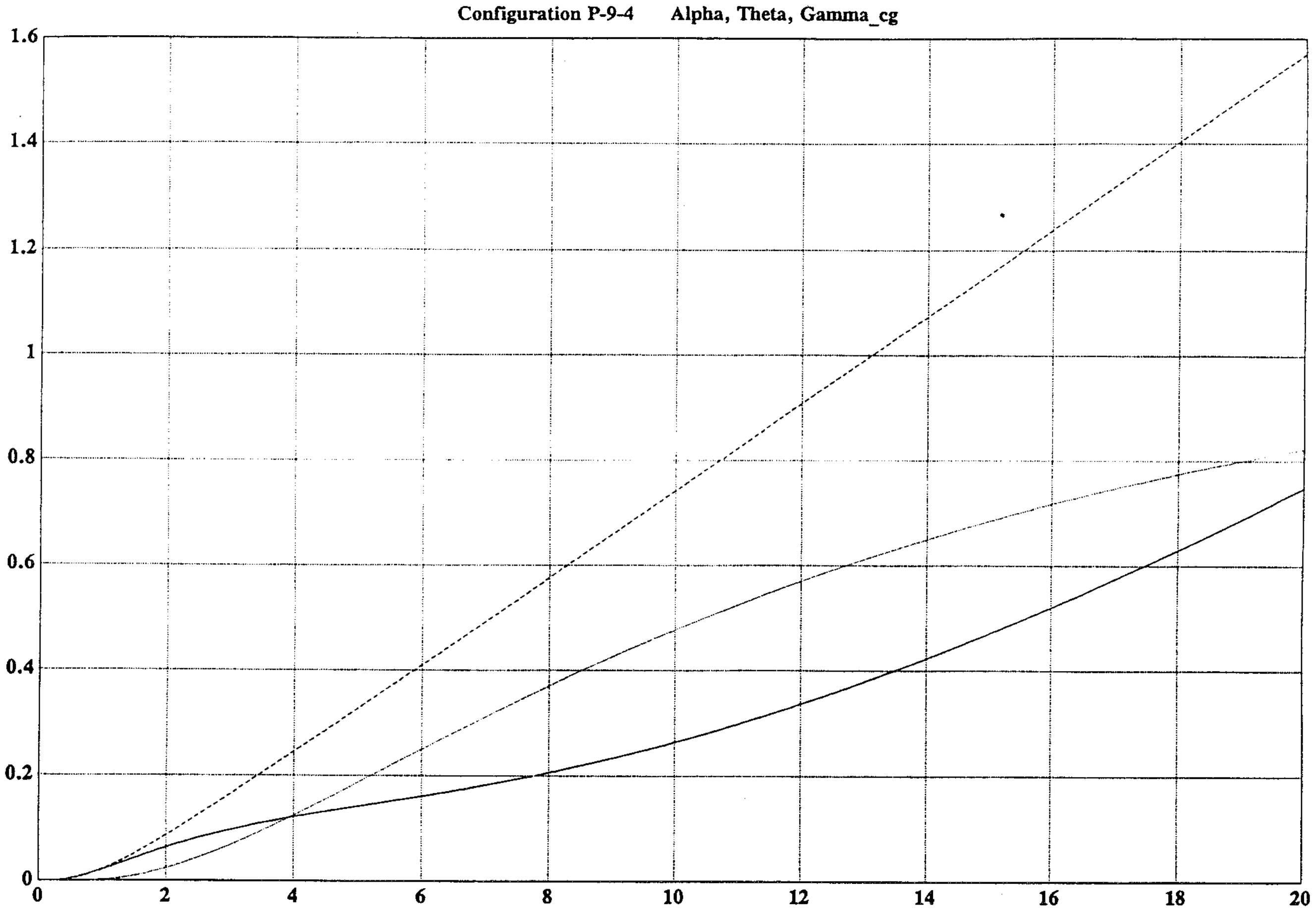

P-9-3 theta rate


P-9-3 gamma_cg

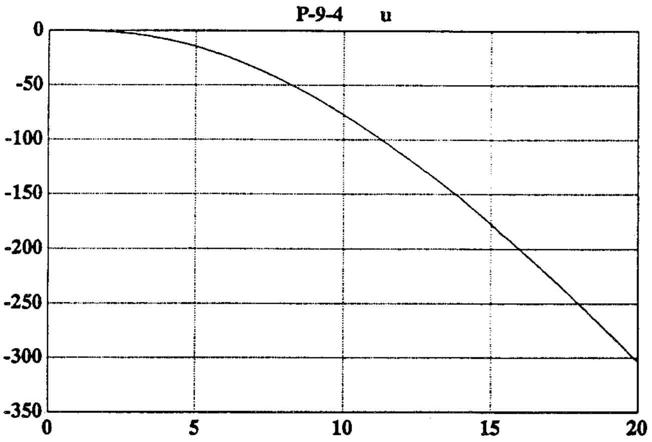

P-9-3 gamma_cg rate


P-9-3 gamma_p

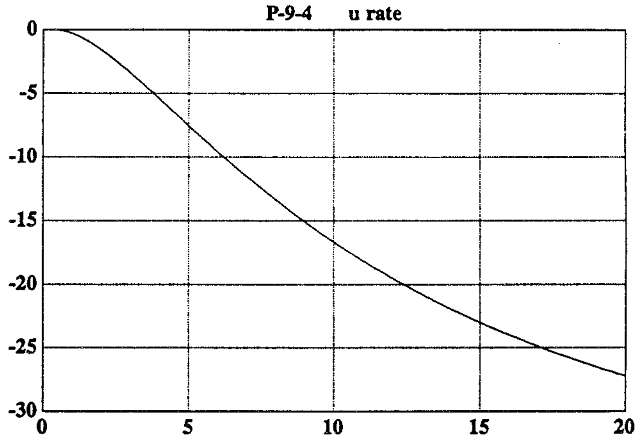

P-9-3 gamma_p rate



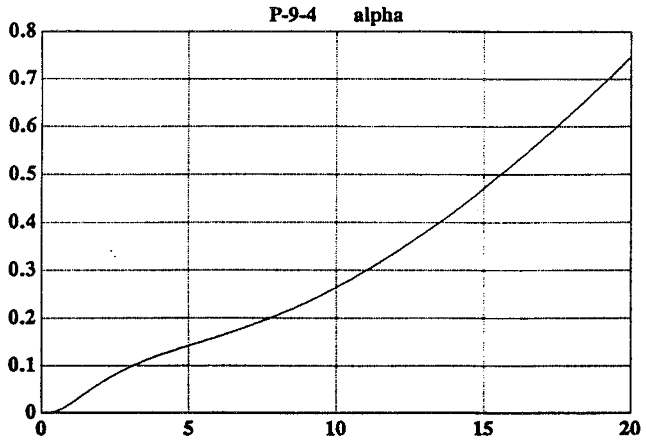
Configuration P-9-4 Alpha, Theta, Gamma_cg



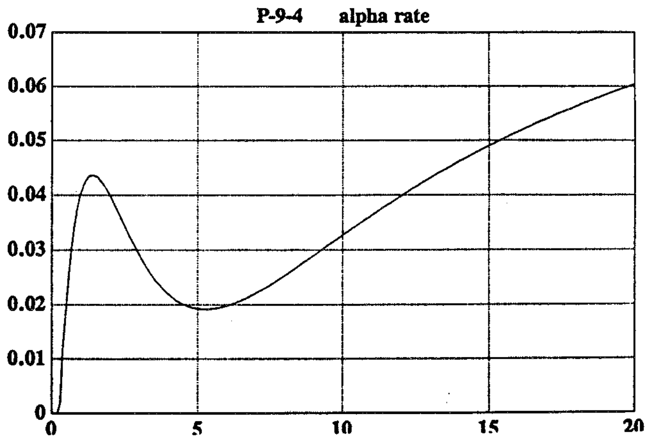
P-9-4 u



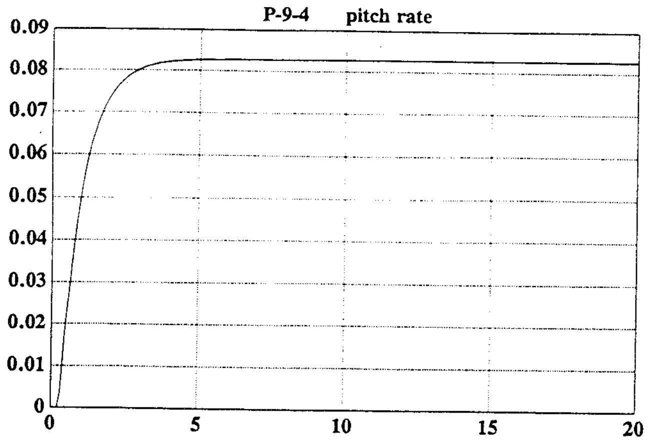
P-9-4 u rate

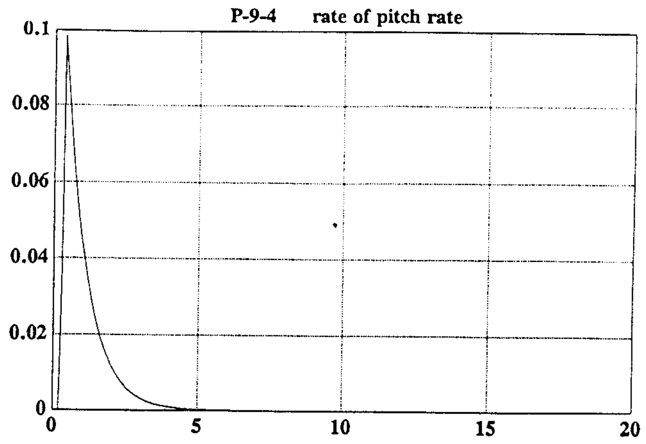


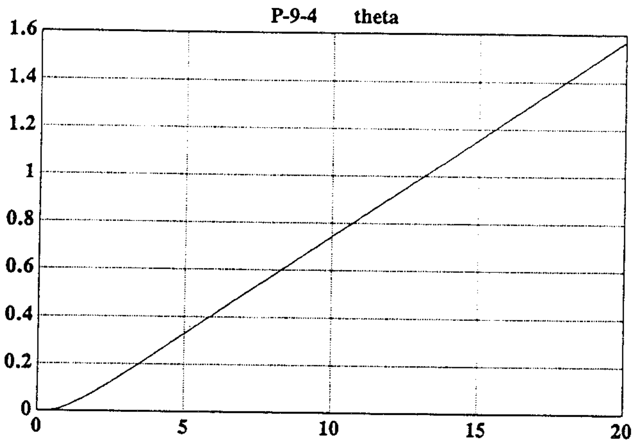
P-9-4 alpha

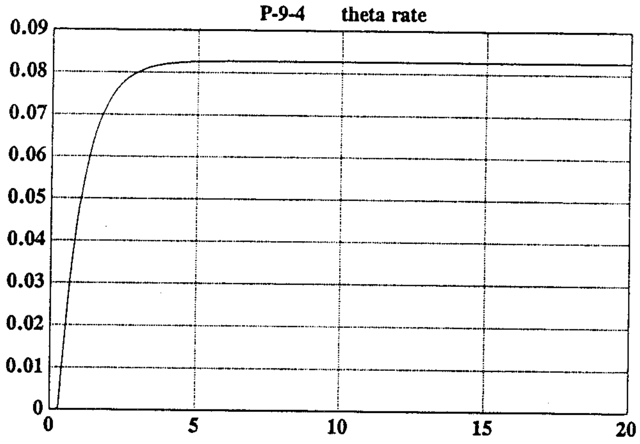


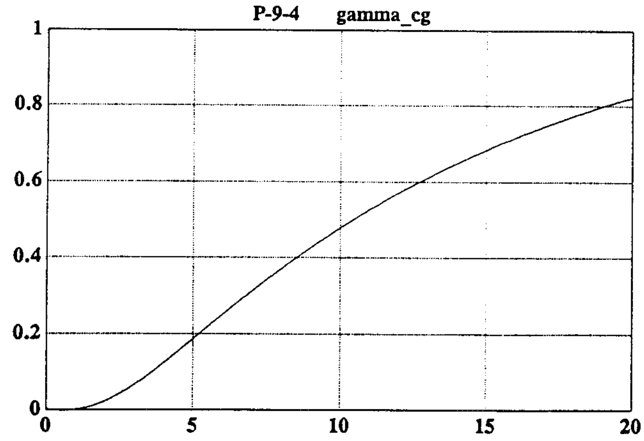
P-9-4 alpha rate

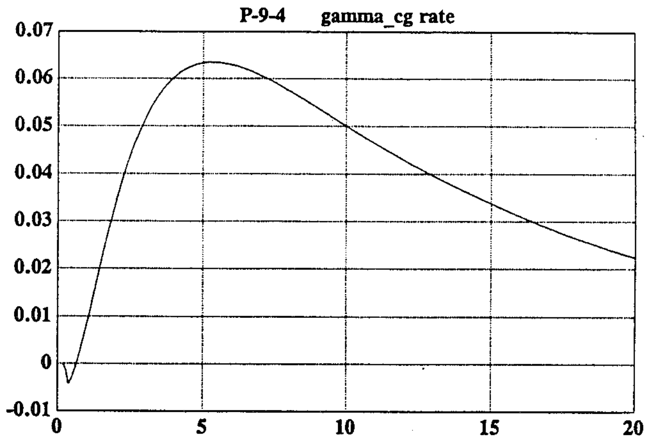

P-9-4 pitch rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

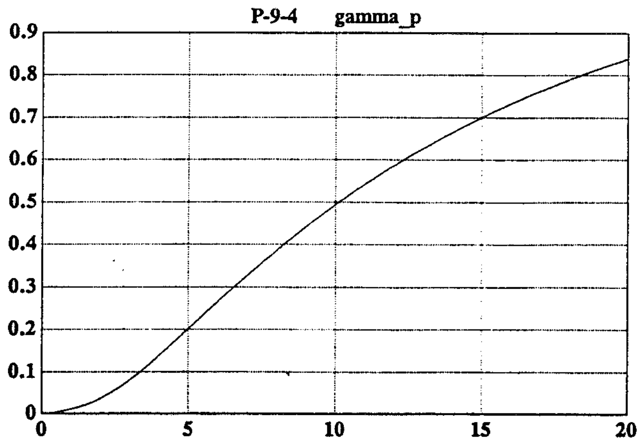

P-9-4 rate of pitch rate
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

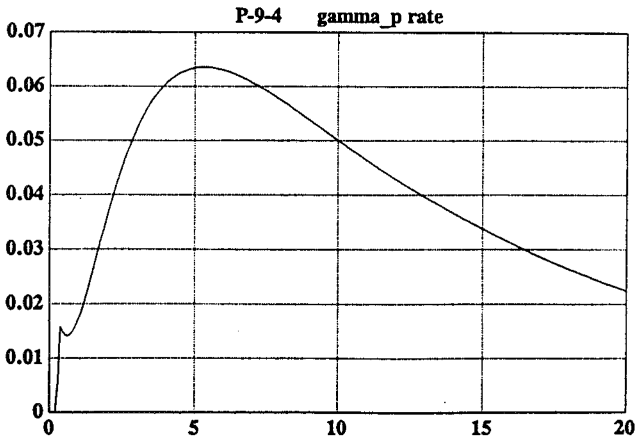

P-9-4 theta
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20


P-9-4 theta rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20


P-9-4 gamma_cg
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20

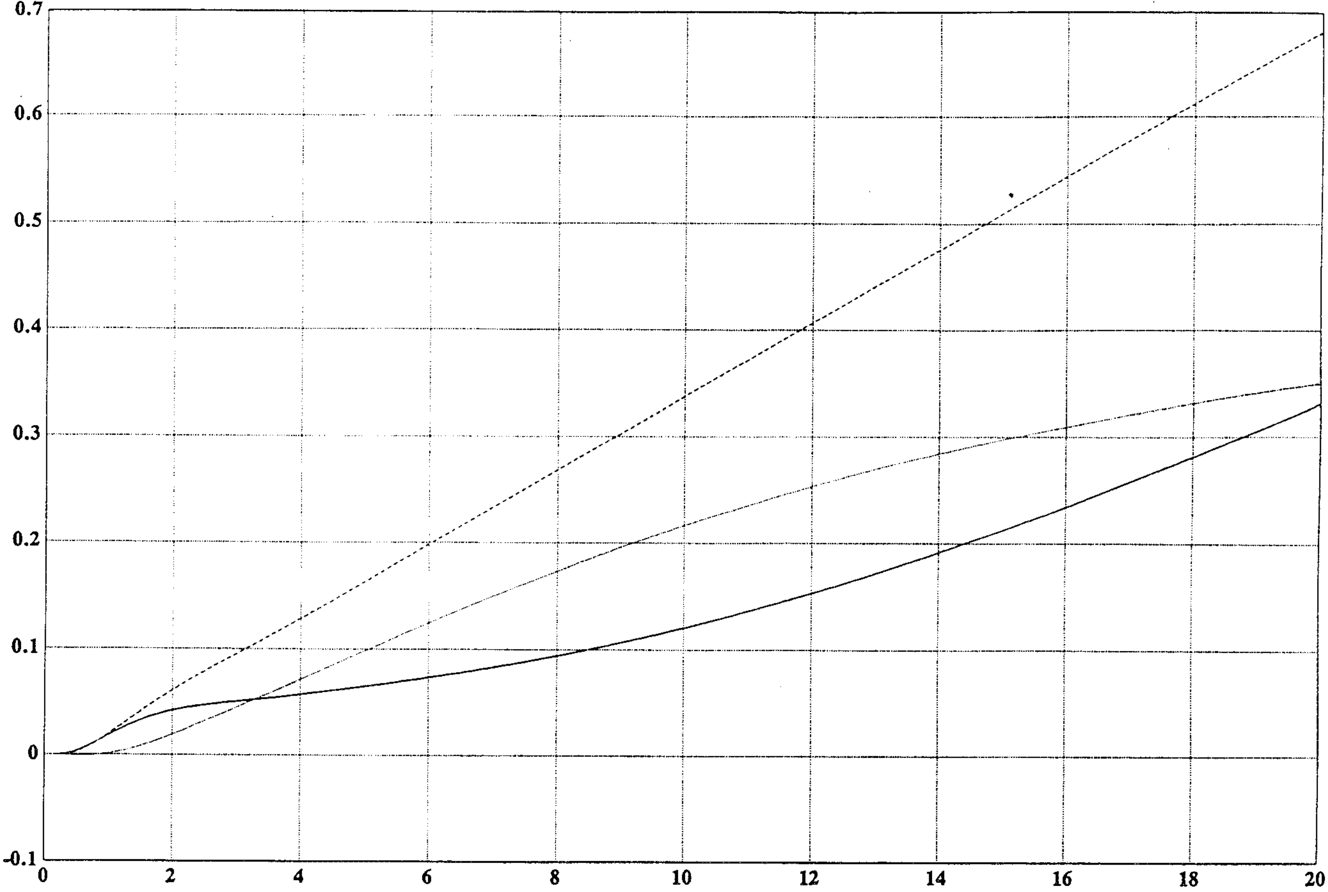

P-9-4 gamma_cg rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

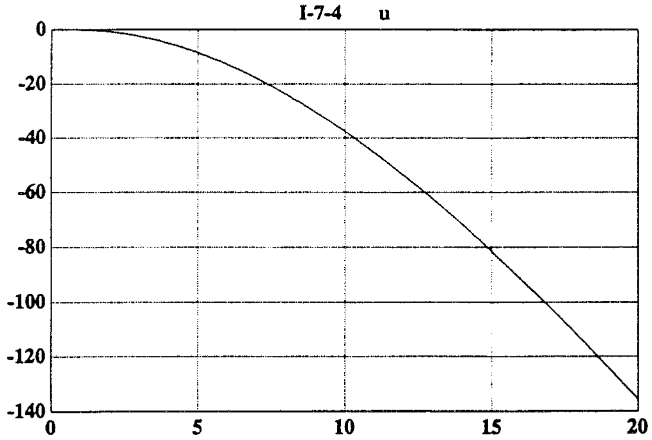

P-9-4 gamma_p
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

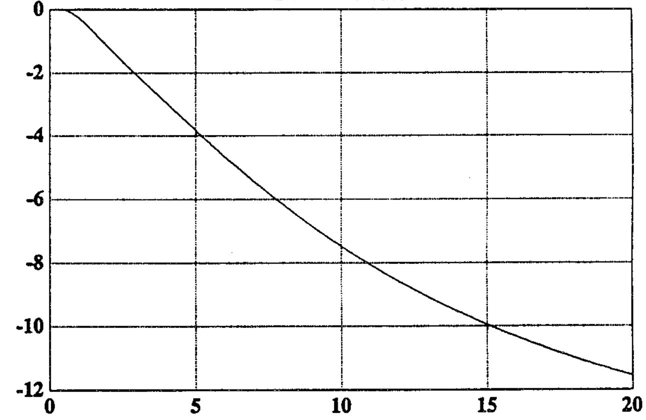

P-9-4 gamma_p rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

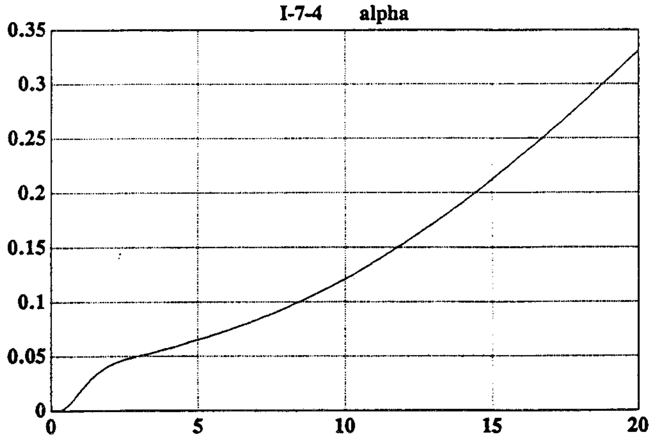
Appendix C

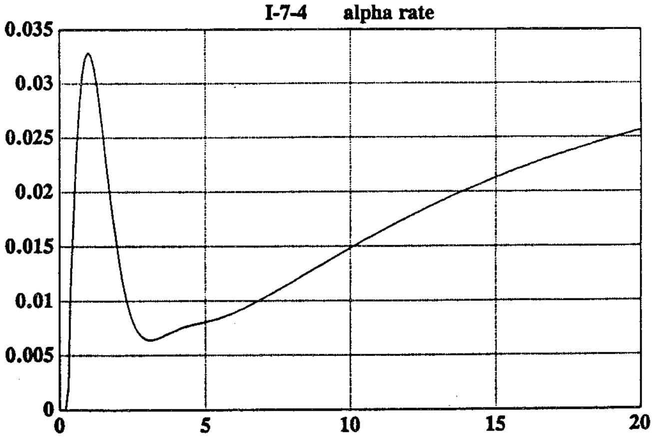
SET I CONFIGURATION TIME HISTORY RESPONSES

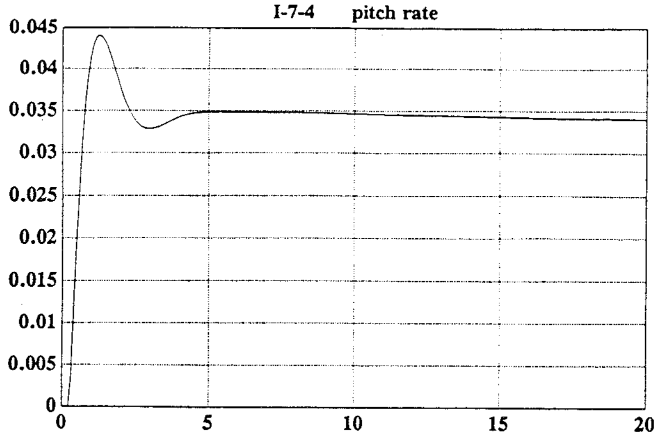

Configuration I-7-4 Alpha, Theta, Gamma_cg

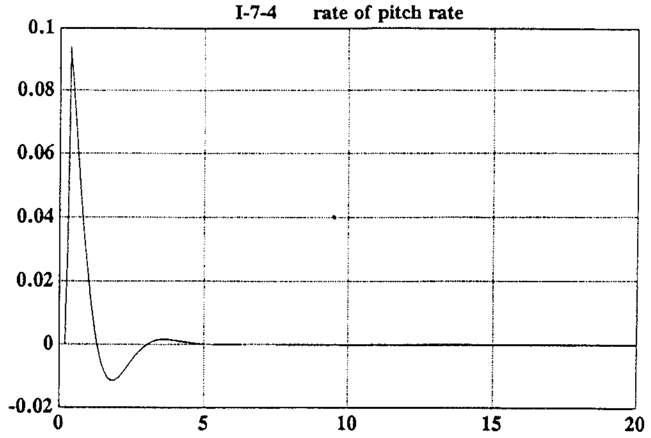

I-7-4 u

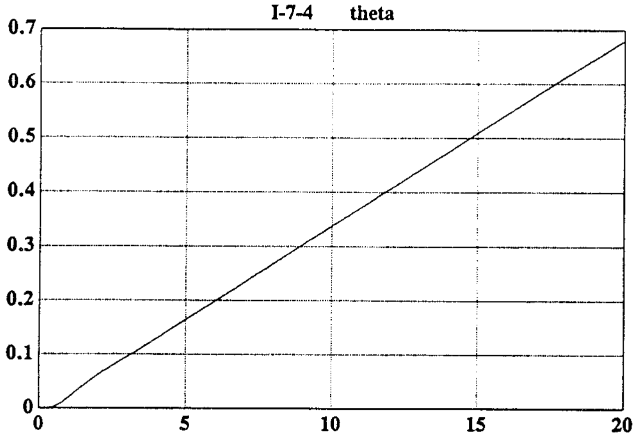

I-7-4 u rate

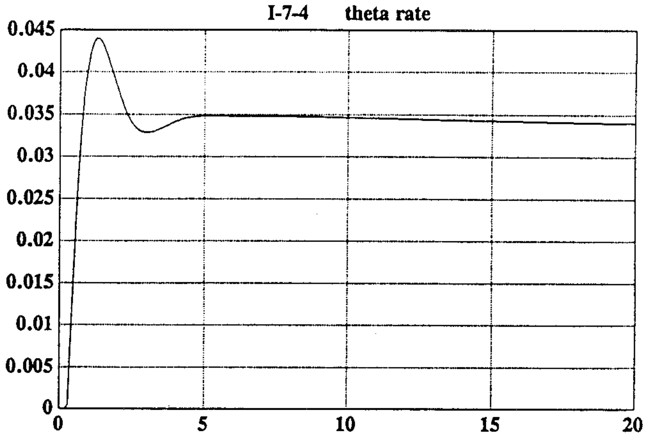

I-7-4 alpha

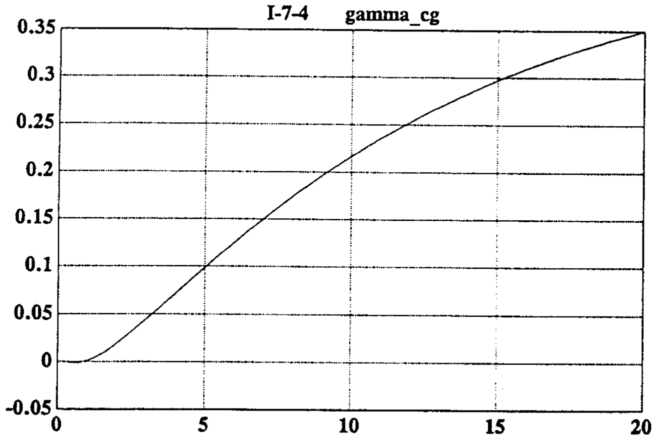

I-7-4 alpha rate

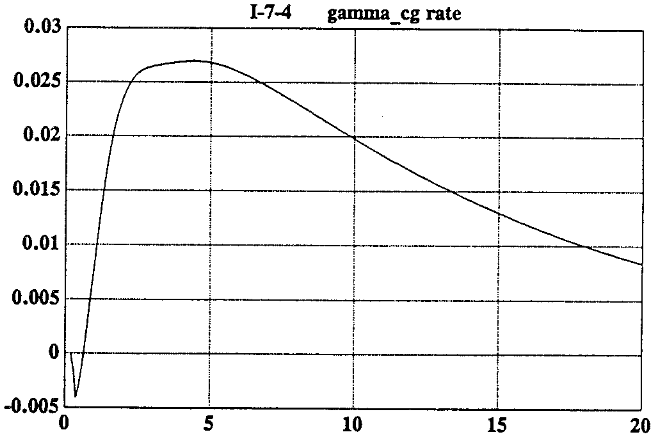

I-7-4 pitch rate
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

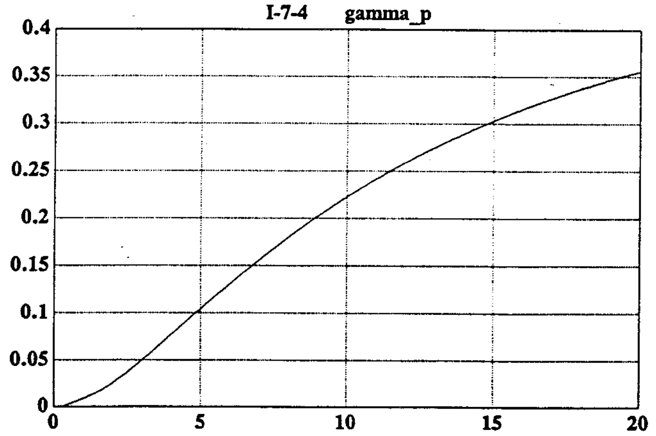

I-7-4 rate of pitch rate
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
5
10
15
20

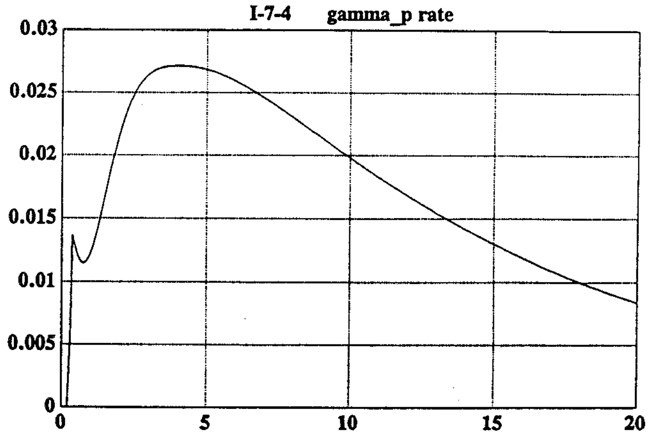

I-7-4 theta
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20


I-7-4 theta rate
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

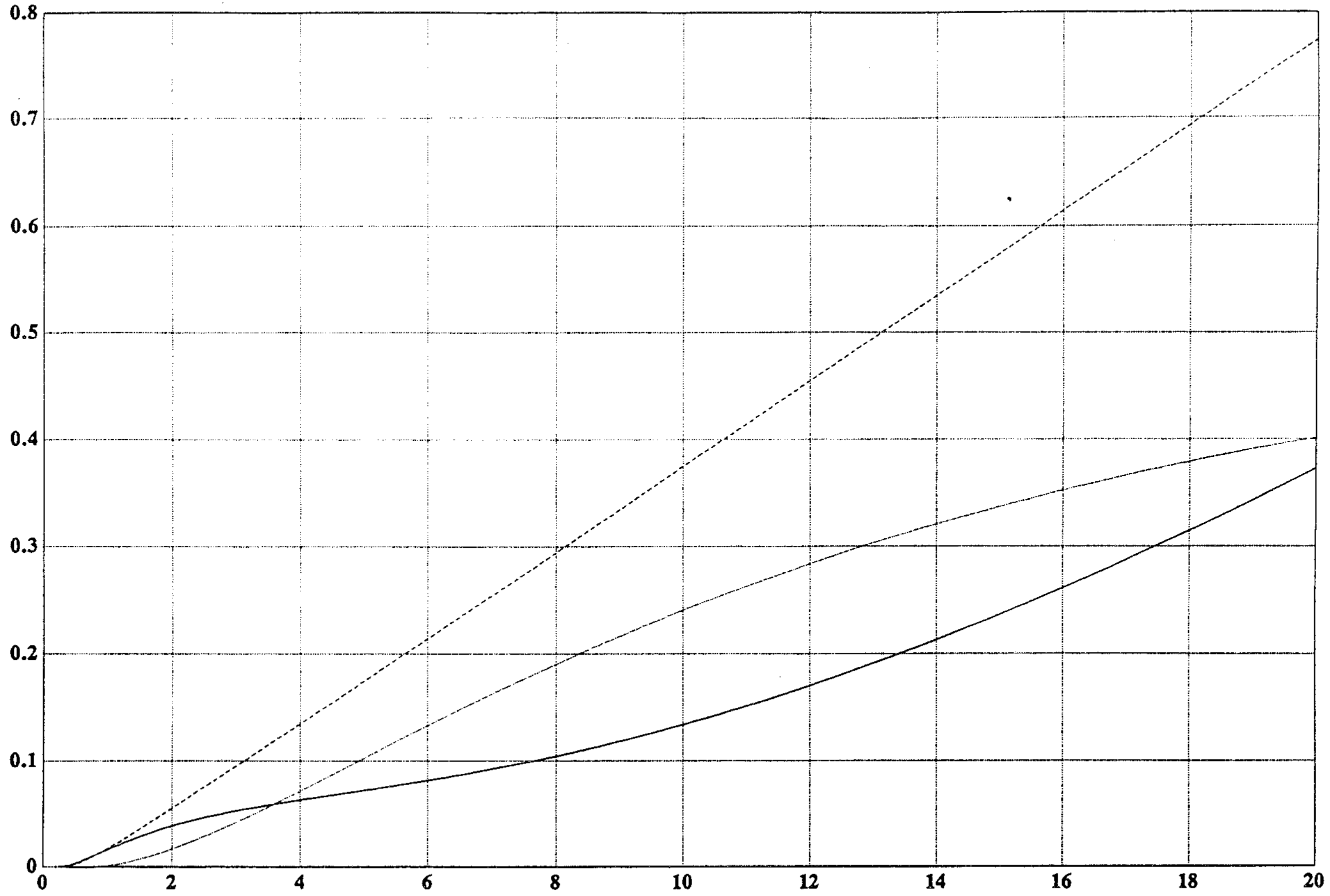

I-7-4 gamma_cg
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
15
20


I-7-4 gamma_cg rate
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
5
10
15
20

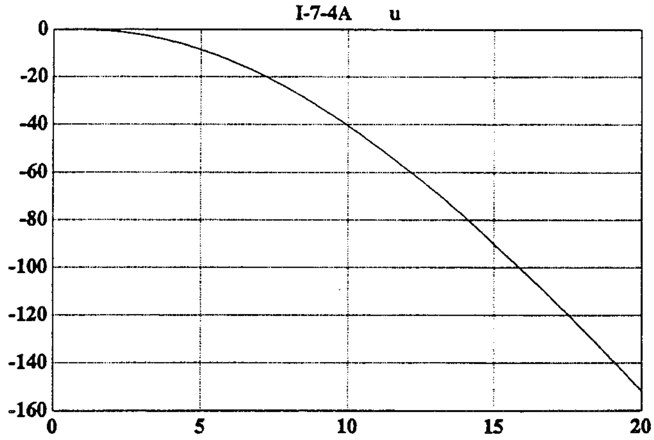

I-7-4 gamma_p
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20


I-7-4 gamma_p rate
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

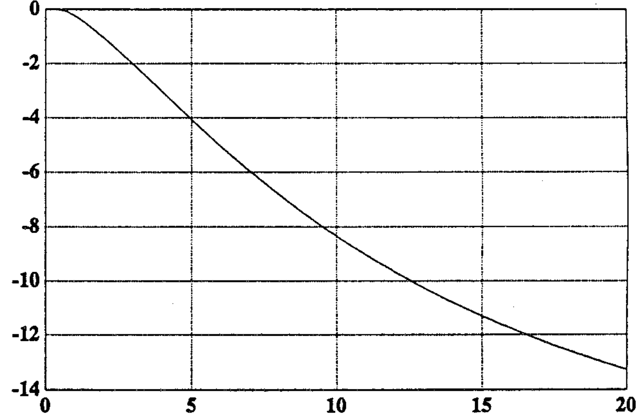
Configuration I-7-4A Alpha, Theta, Gamma_cg



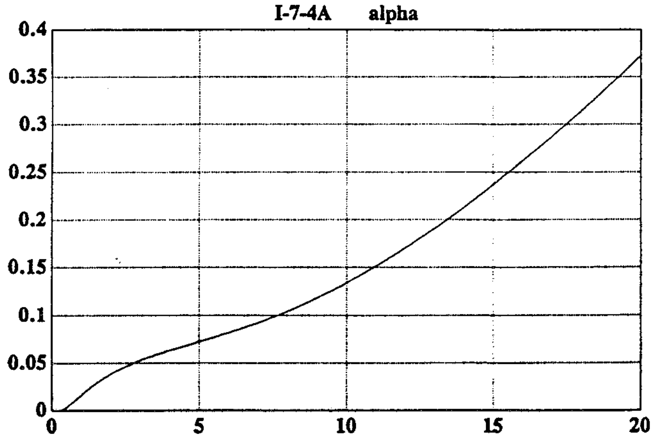
I-7-4A u



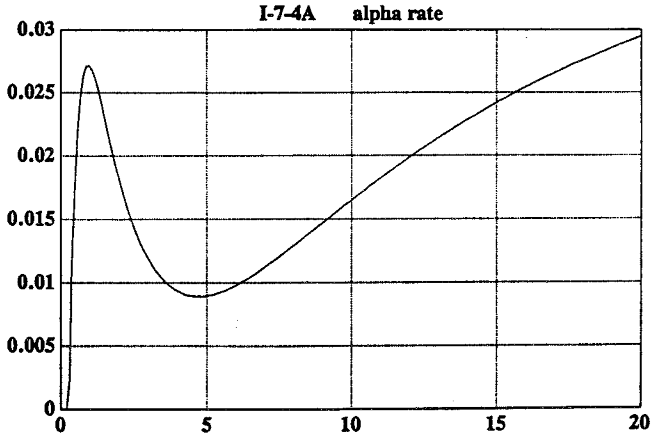
I-7-4A u rate

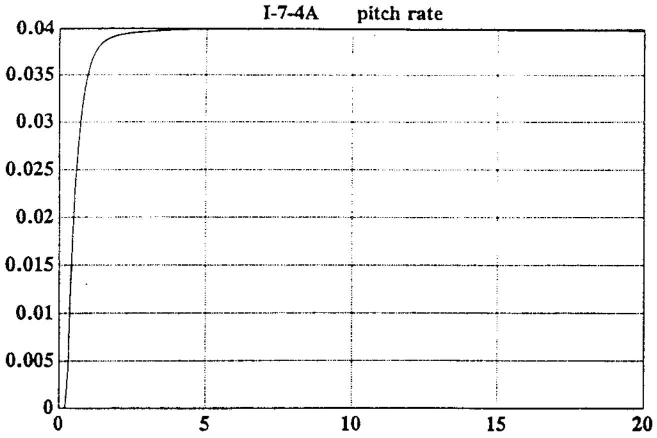


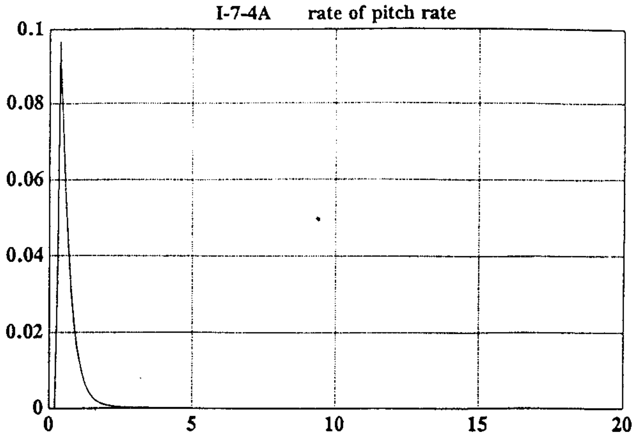
I-7-4A alpha

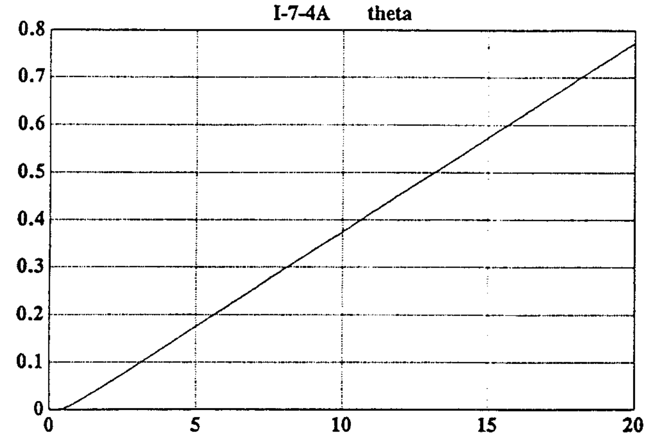


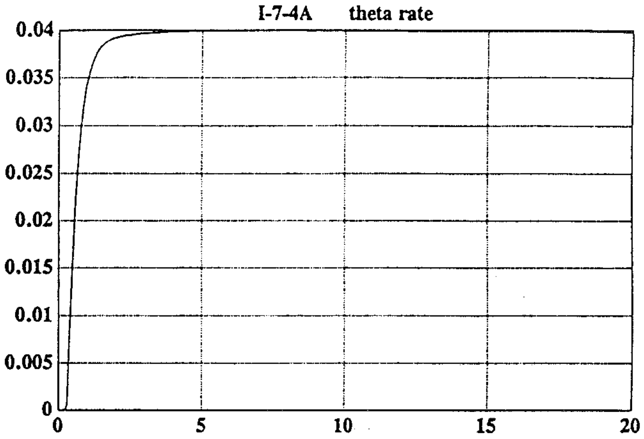
I-7-4A alpha rate

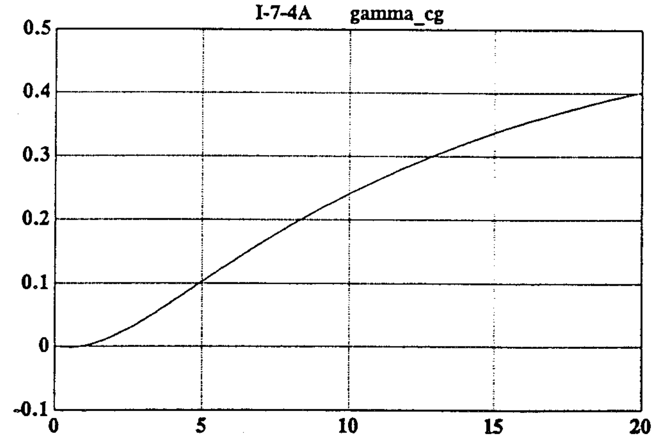


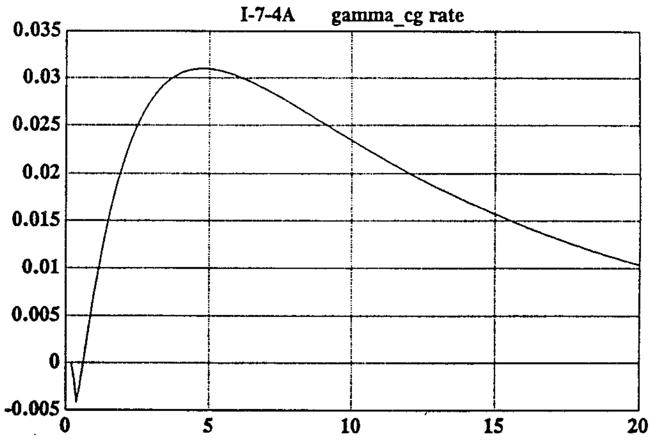

I-7-4A pitch rate

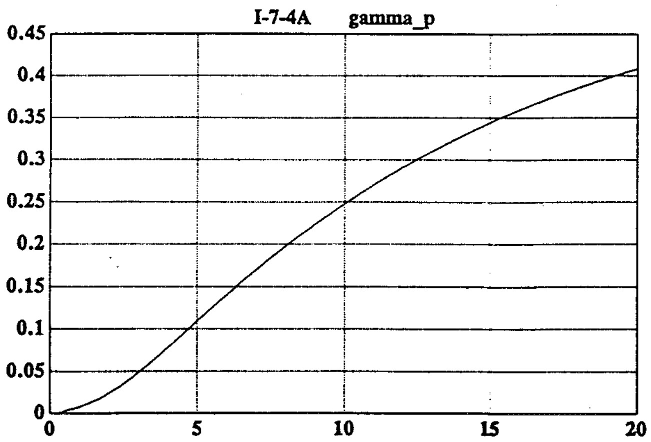

I-7-4A rate of pitch rate

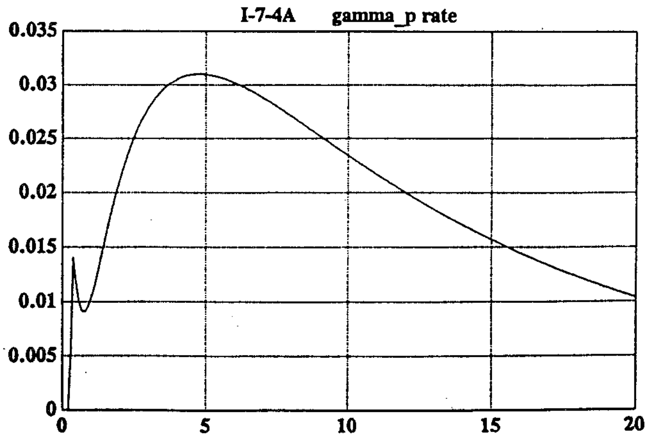

I-7-4A theta

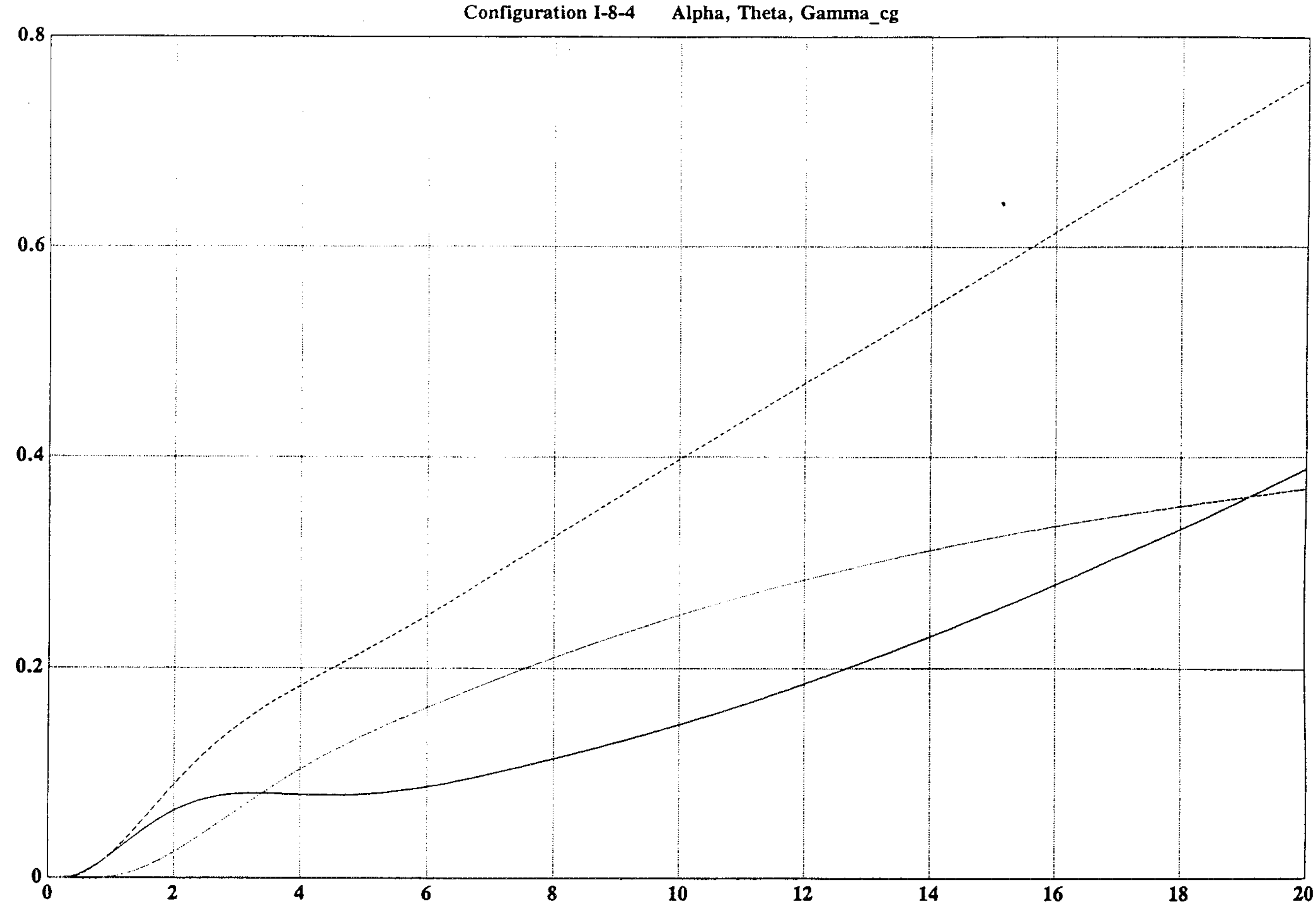

I-7-4A theta rate

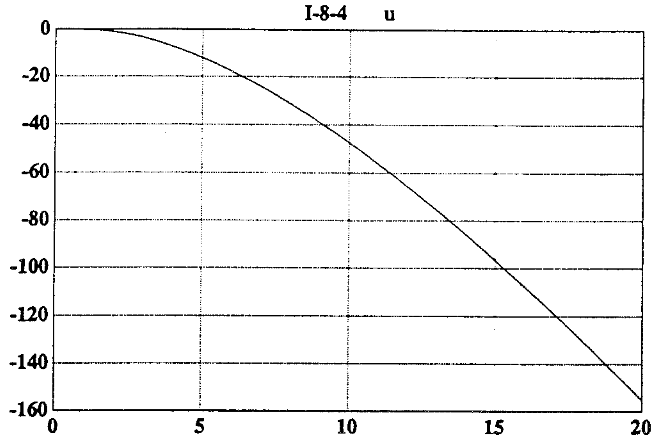

I-7-4A gamma_cg

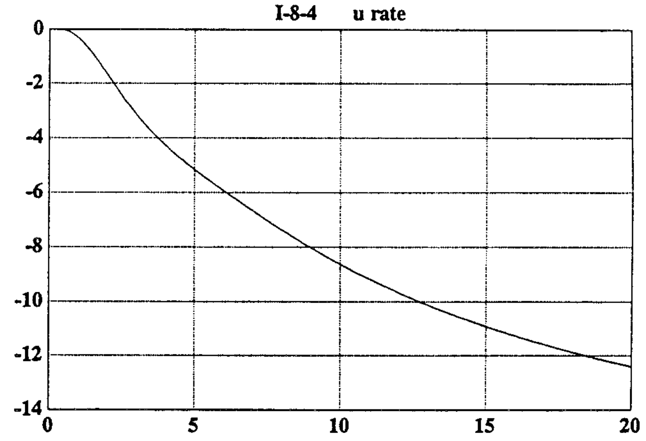

I-7-4A gamma_cg rate

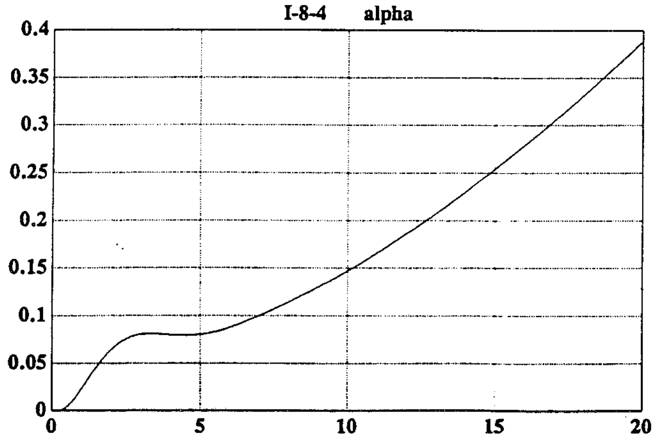

I-7-4A gamma_p

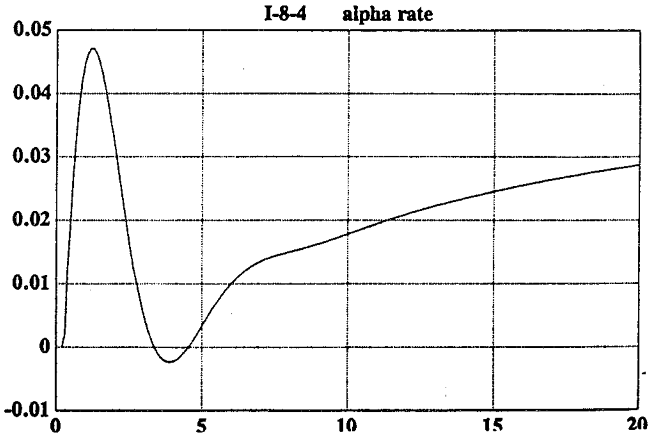

I-7-4A gamma_p rate

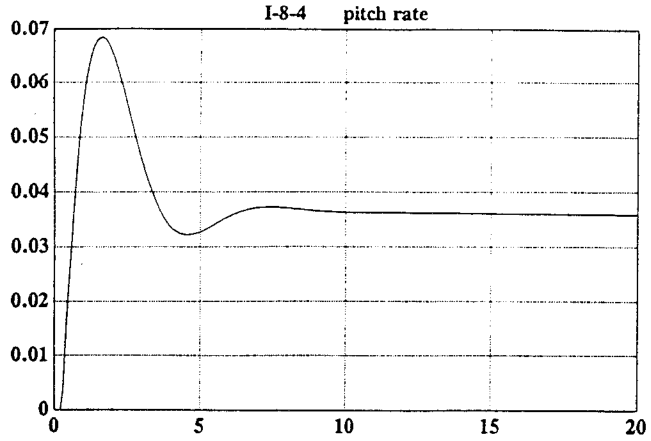

Configuration I-8-4 Alpha, Theta, Gamma_cg
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

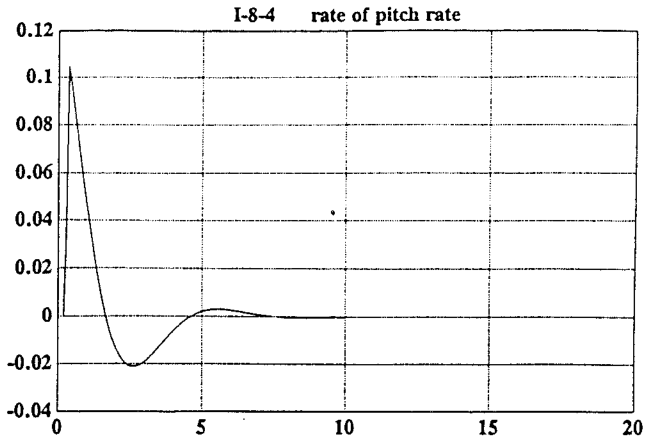

I-8-4 u
0
-20
-40
-60
-80
-100
-120
-140
-160
0
5
10
15
20

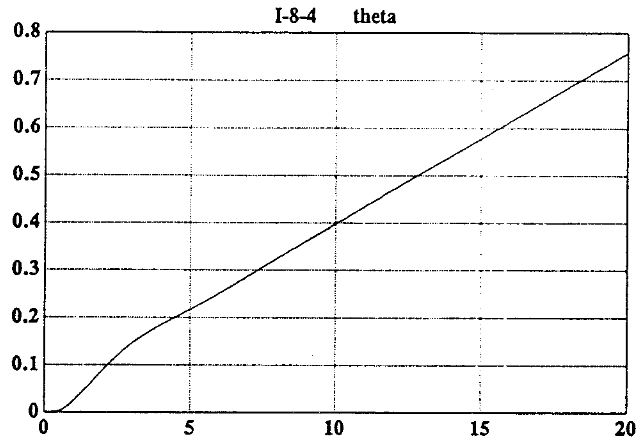

I-8-4 u rate
0
-2
-4
-6
-8
-10
-12
-14
0
5
10
15
20

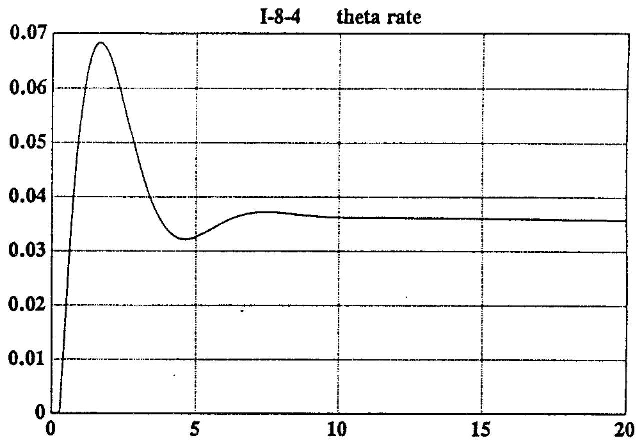

I-8-4 alpha
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20

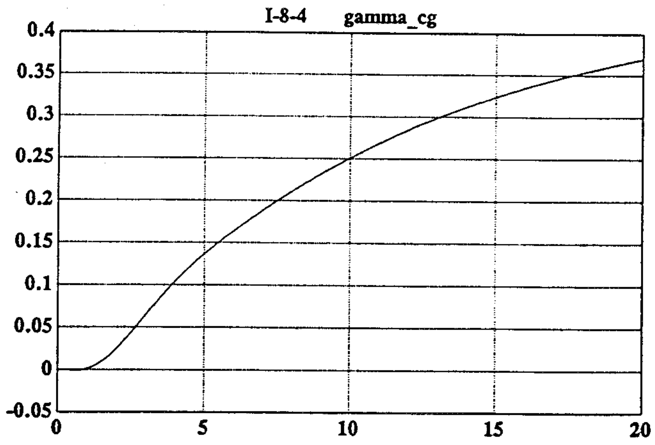

I-8-4 alpha rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

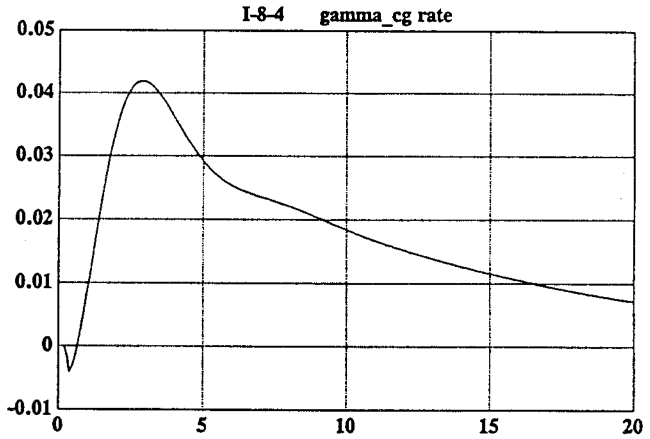

I-8-4 pitch rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

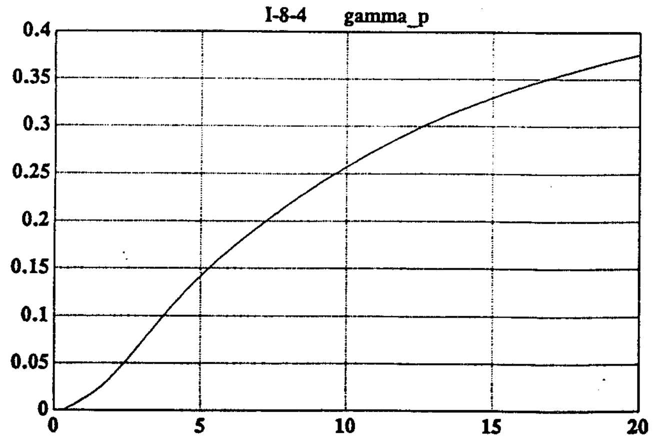

I-8-4 rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

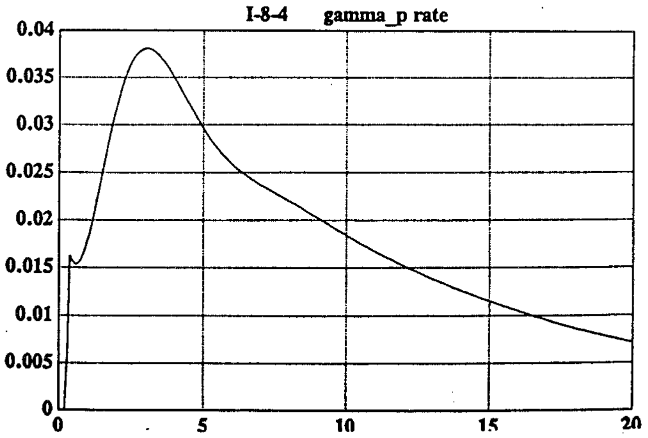

I-8-4 theta
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

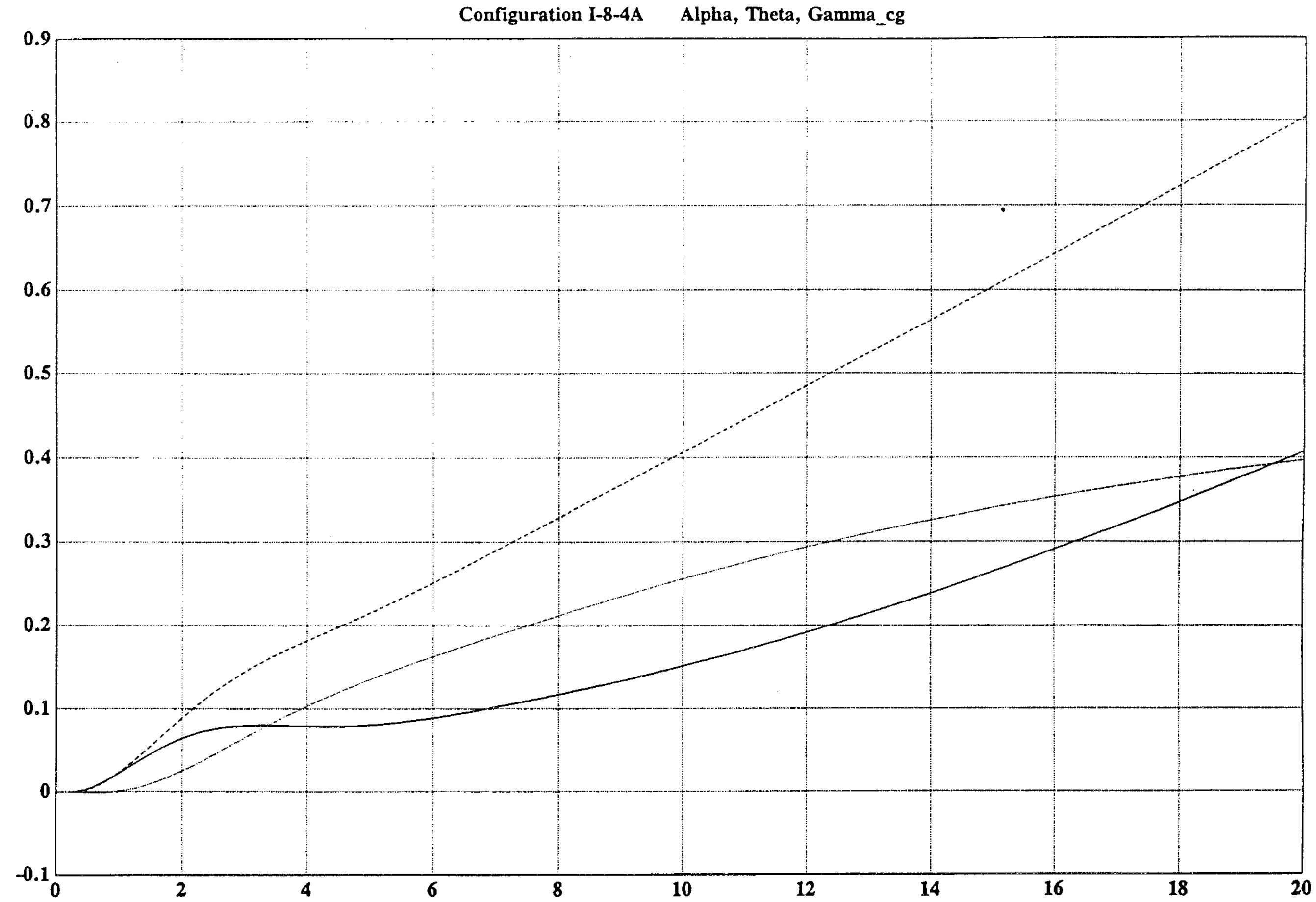

I-8-4 theta rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

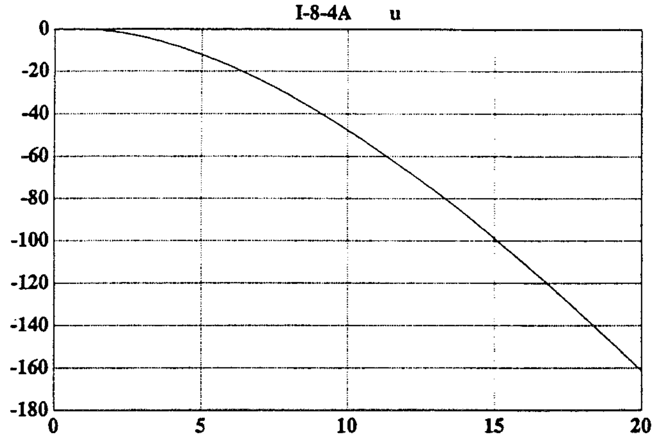

I-8-4 gamma_cg
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
15
20

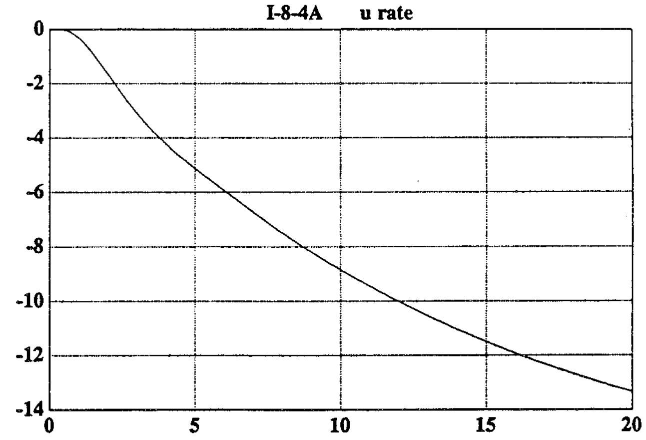

I-8-4 gamma_cg rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

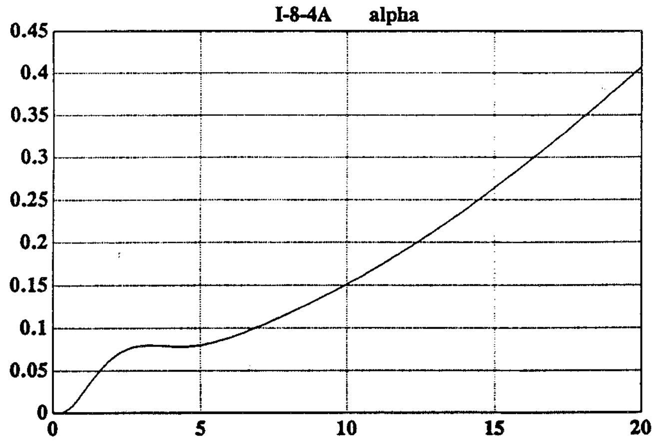

I-8-4 gamma_p
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20

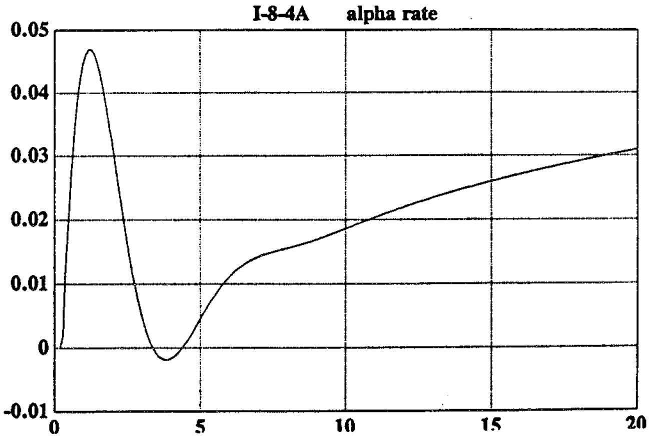

I-8-4 gamma_p rate
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

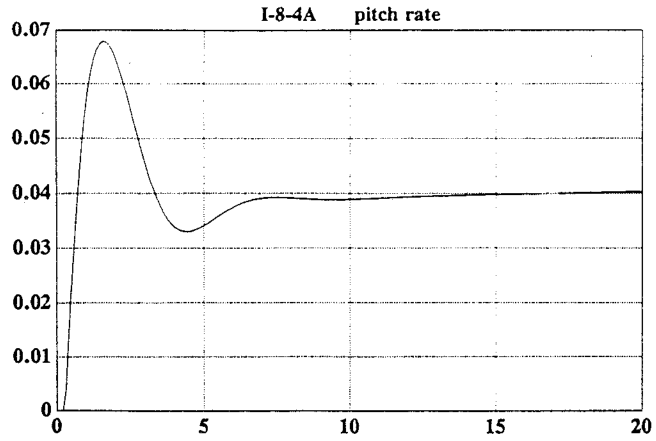

Configuration I-8-4A Alpha, Theta, Gamma_cg

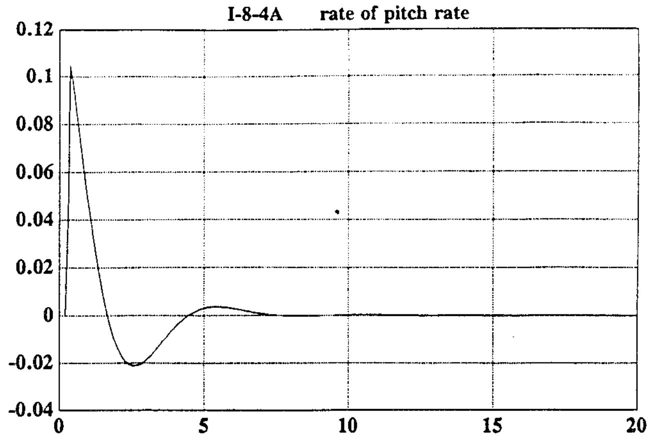

I-8-4A u

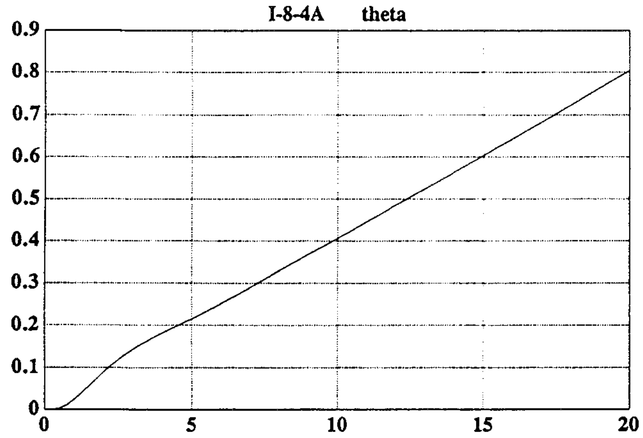

I-8-4A u rate

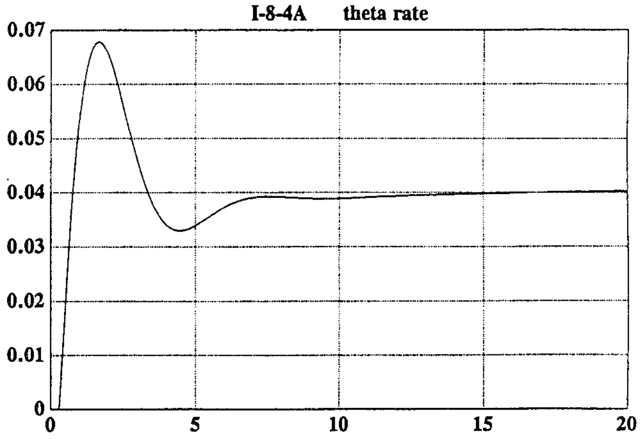

I-8-4A alpha

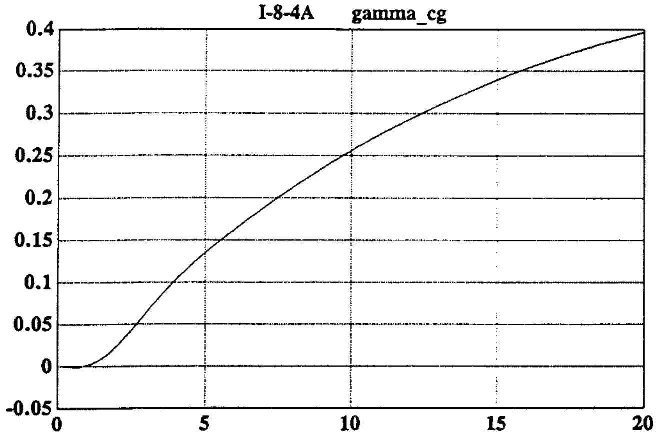

I-8-4A alpha rate

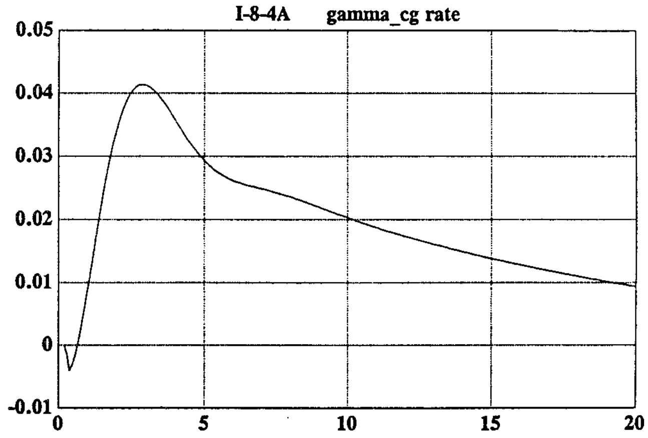

I-8-4A pitch rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

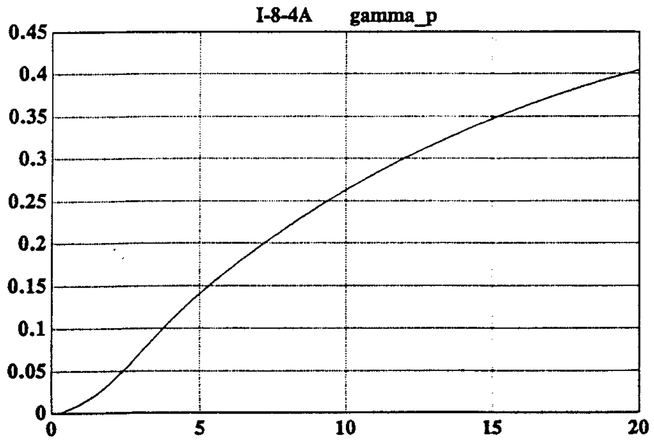

I-8-4A rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

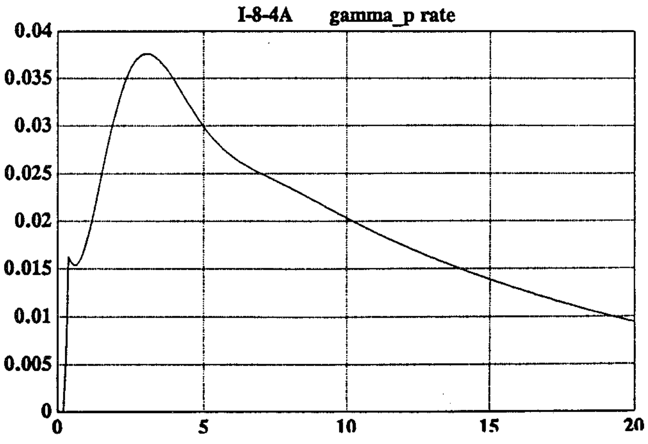

I-8-4A theta
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

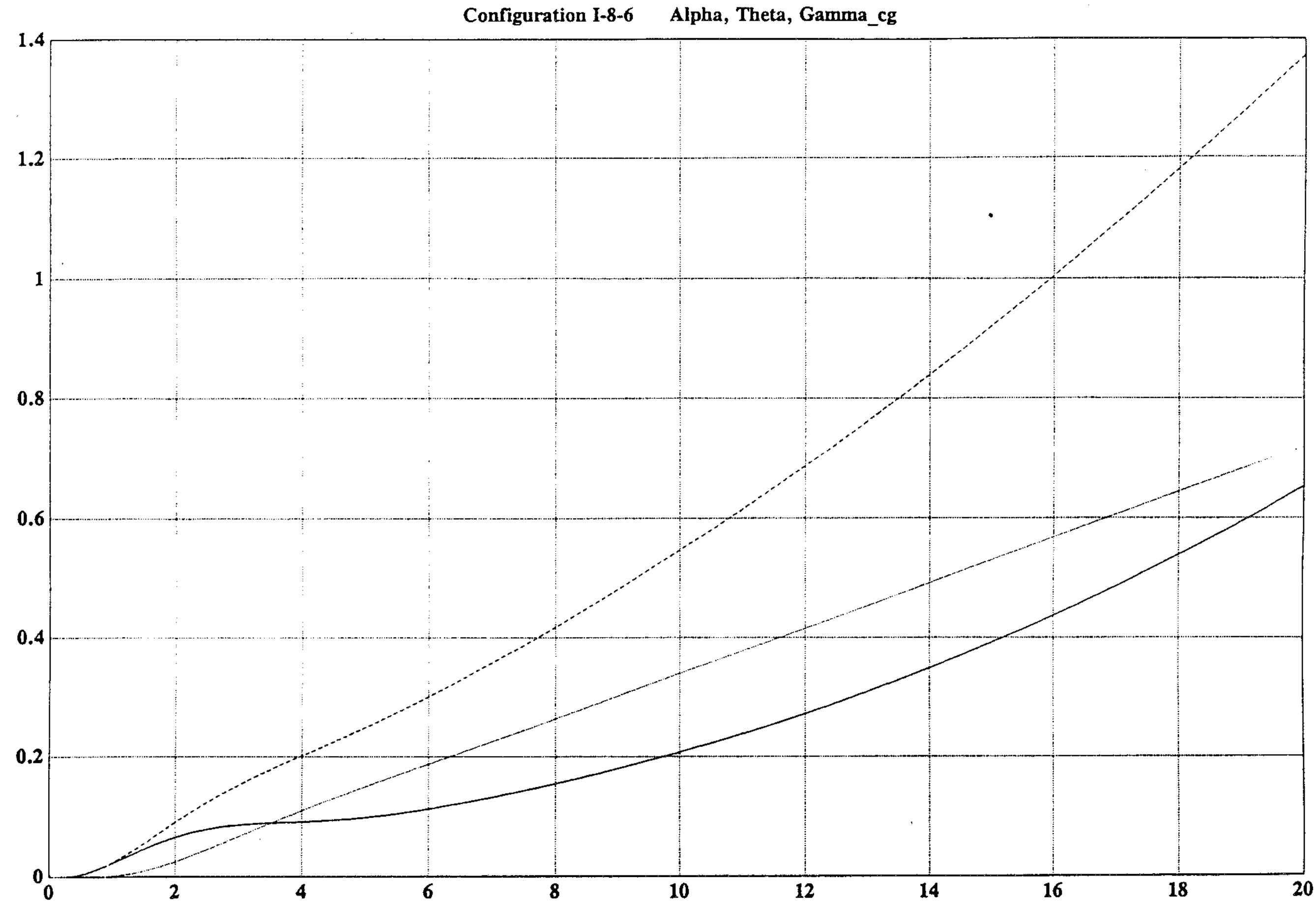

I-8-4A theta rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

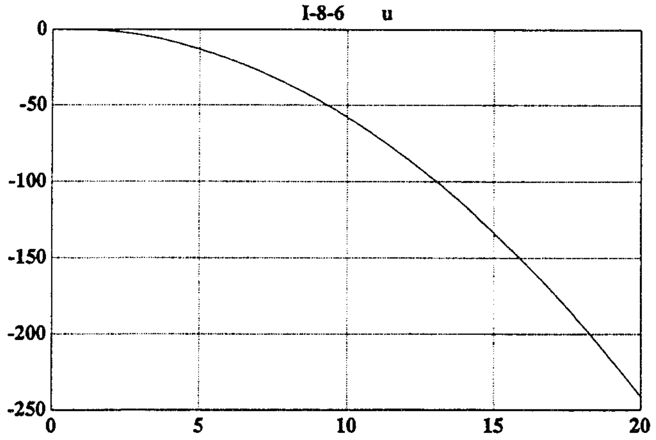

I-8-4A gamma_cg
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
15
20

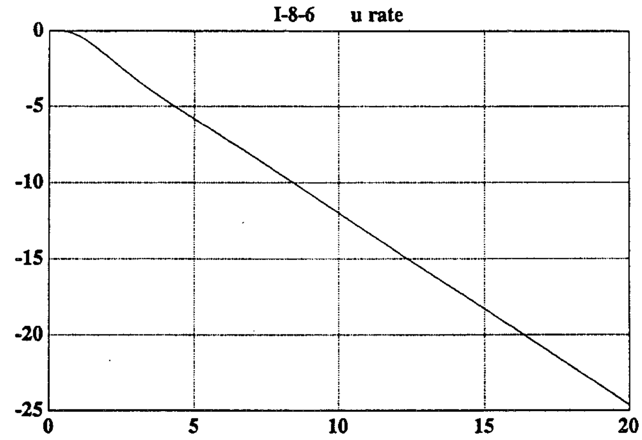

I-8-4A gamma_cg rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

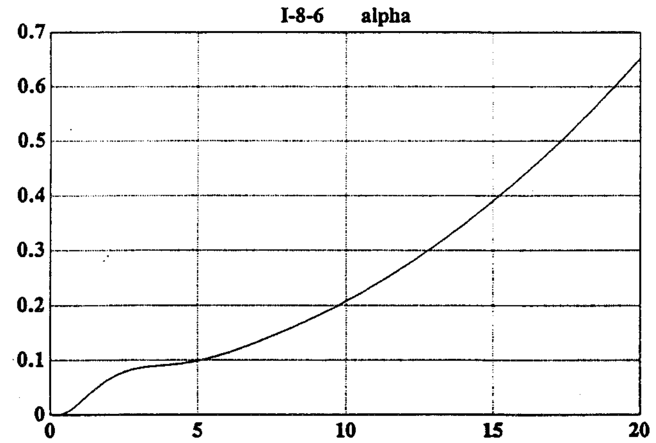

I-8-4A gamma_p
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20

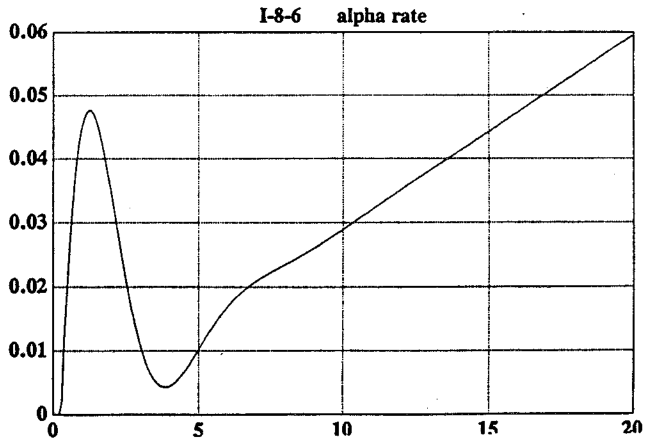

I-8-4A gamma_p rate
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

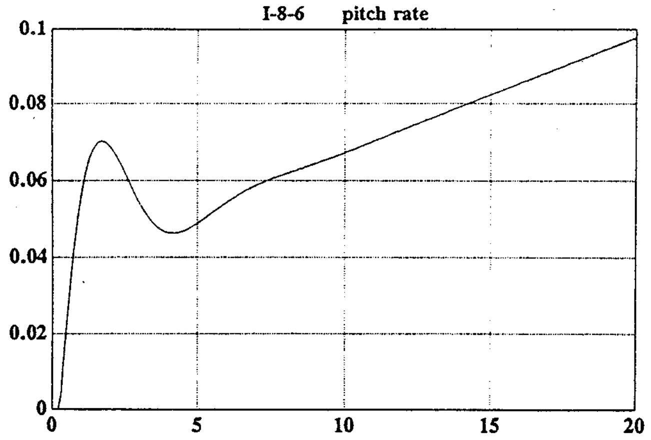

Configuration I-8-6 Alpha, Theta, Gamma_cg
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

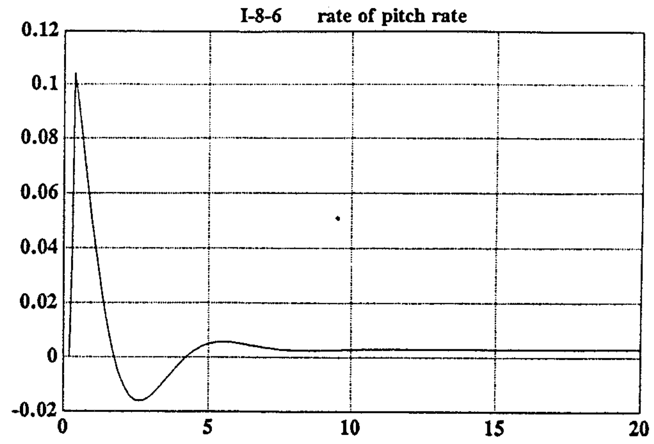

I-8-6 u
0
-50
-100
-150
-200
-250
0
5
10
15
20

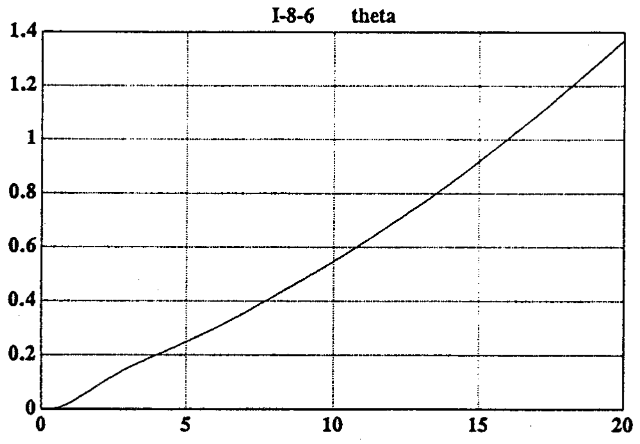

I-8-6 u rate
0
-5
-10
-15
-20
-25
0
5
10
15
20

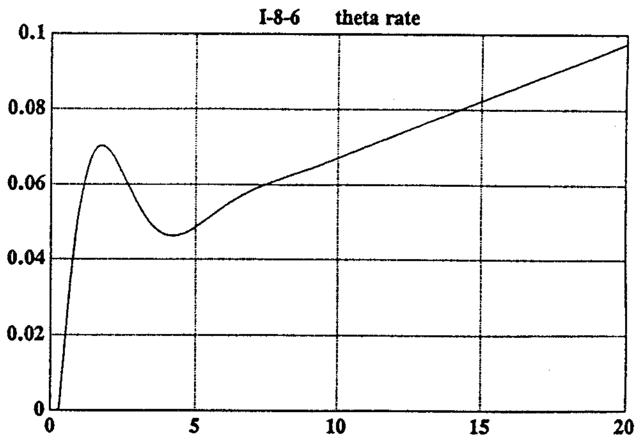

I-8-6 alpha
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

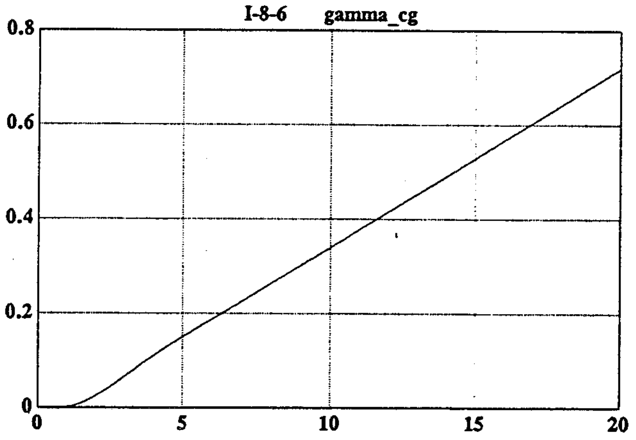

I-8-6 alpha rate
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

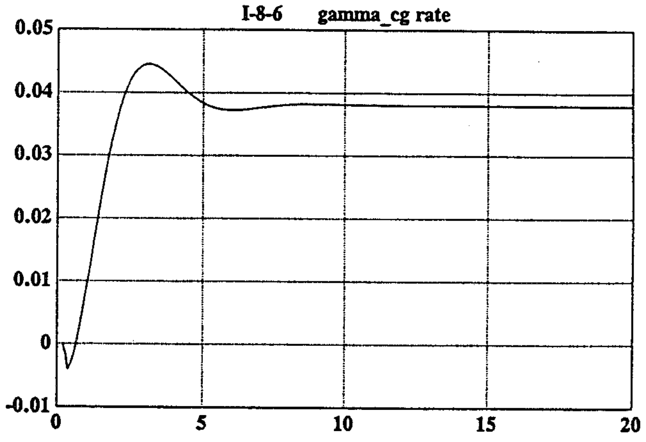

I-8-6 pitch rate

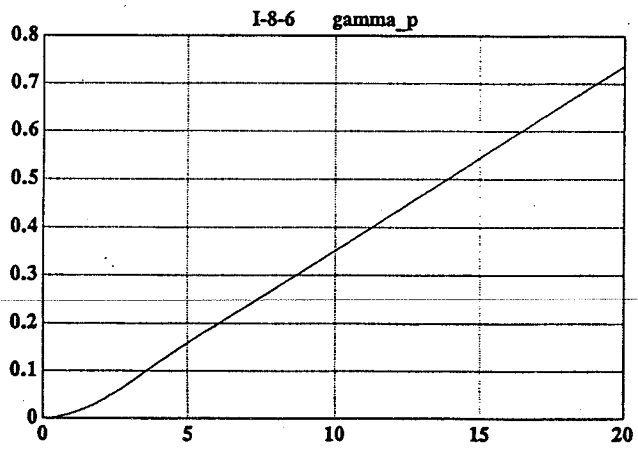

I-8-6 rate of pitch rate

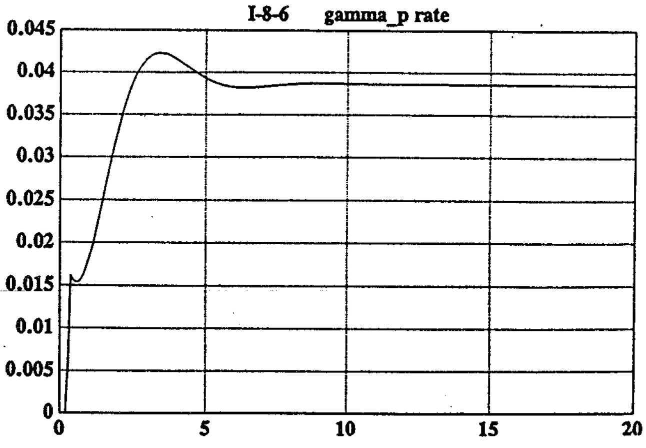

I-8-6 theta

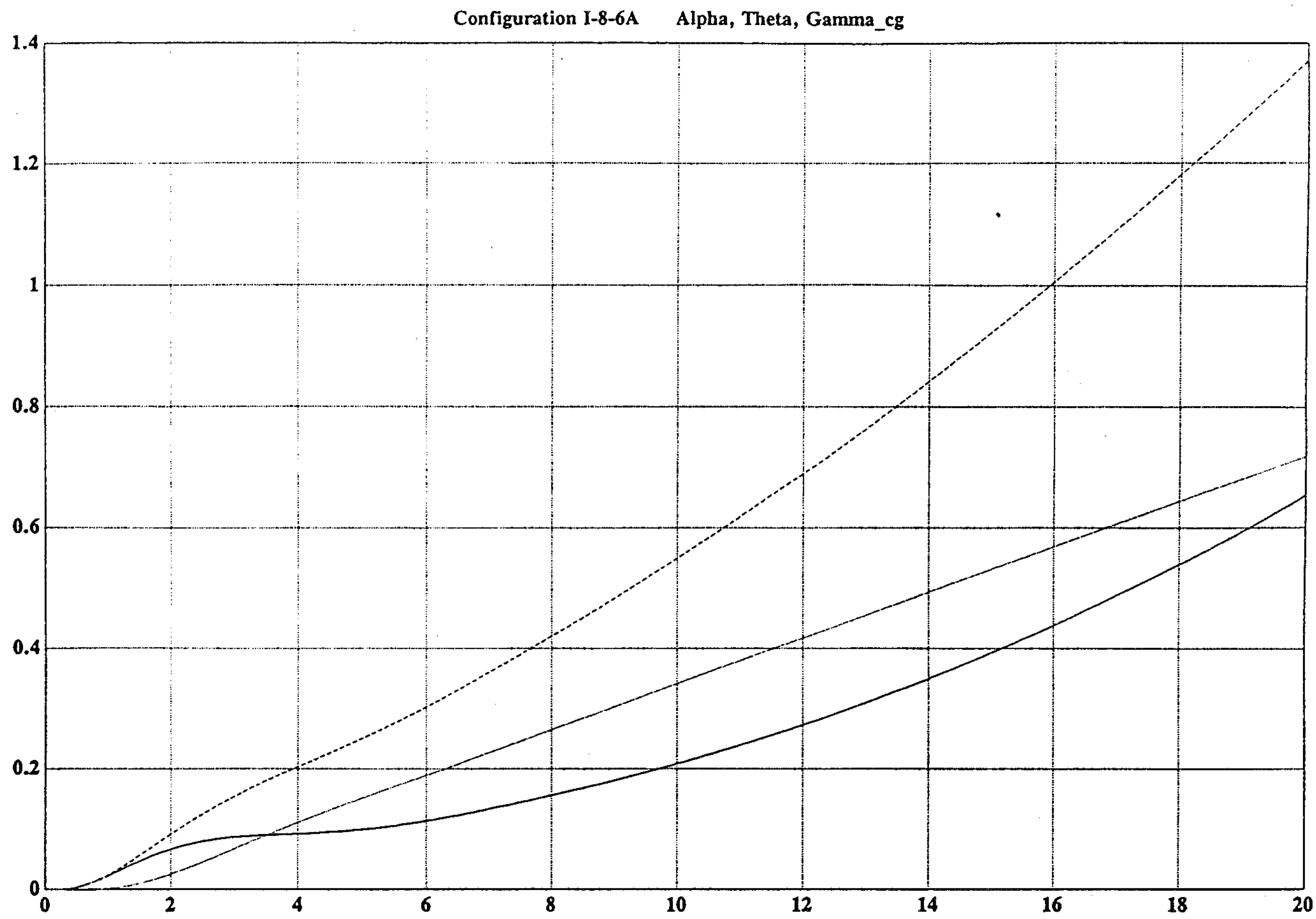

I-8-6 theta rate

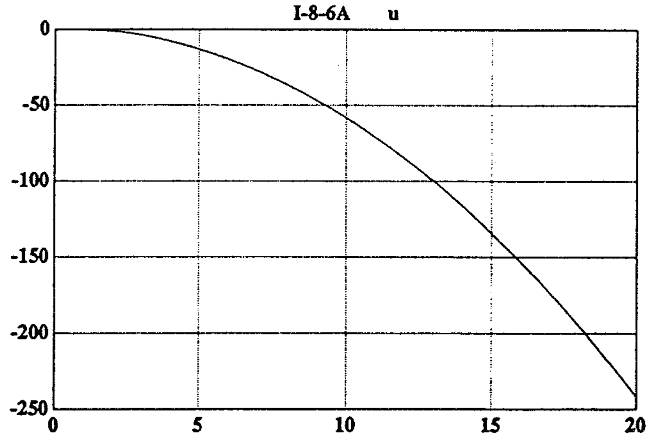

I-8-6 gamma_cg

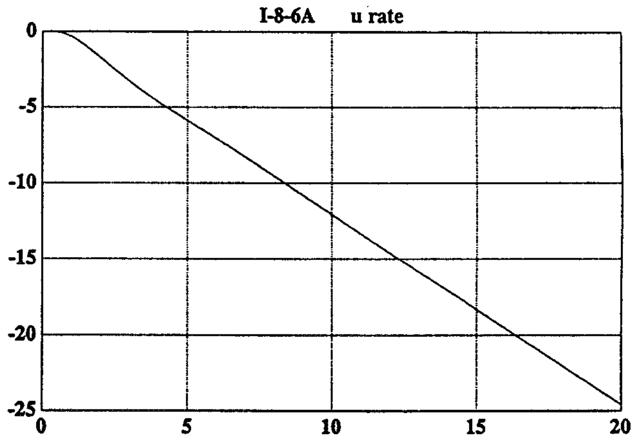

I-8-6 gamma_cg rate

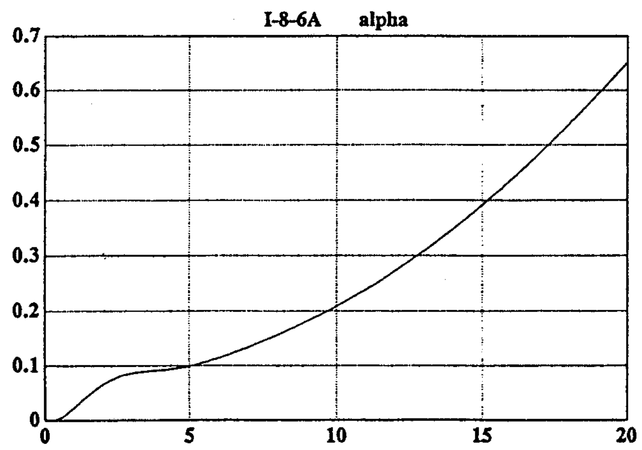

I-8-6 gamma_p

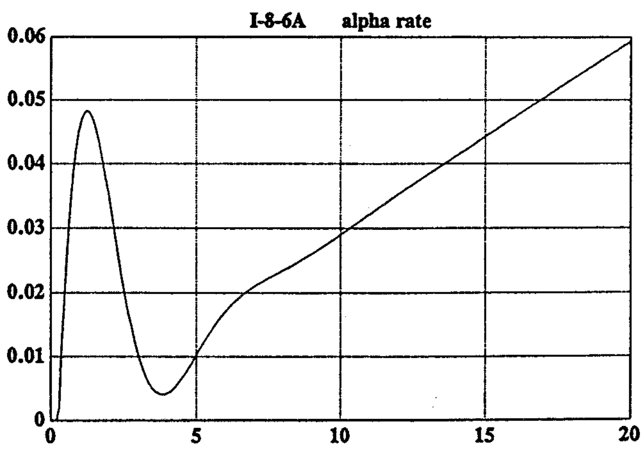

I-8-6 gamma_p rate

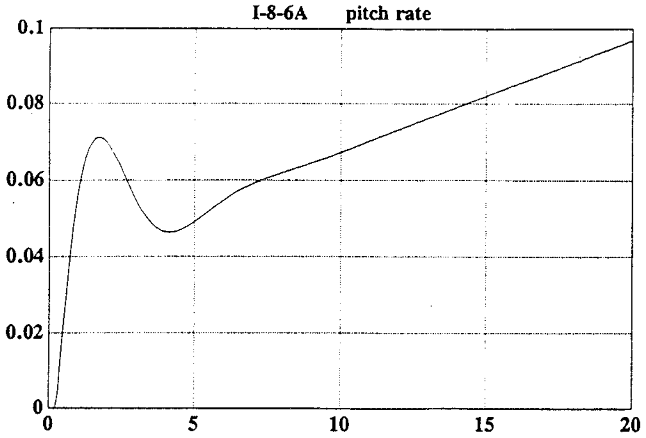

Configuration I-8-6A Alpha, Theta, Gamma_cg
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20


I-8-6A u
0
-50
-100
-150
-200
-250
0
5
10
15
20

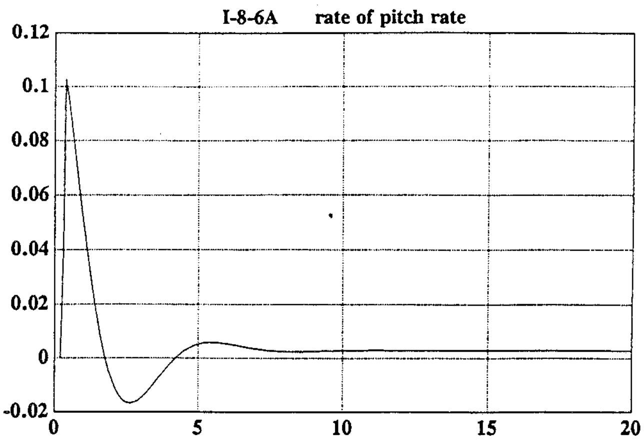

I-8-6A u rate
0
-5
-10
-15
-20
-25
0
5
10
15
20


I-8-6A alpha
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

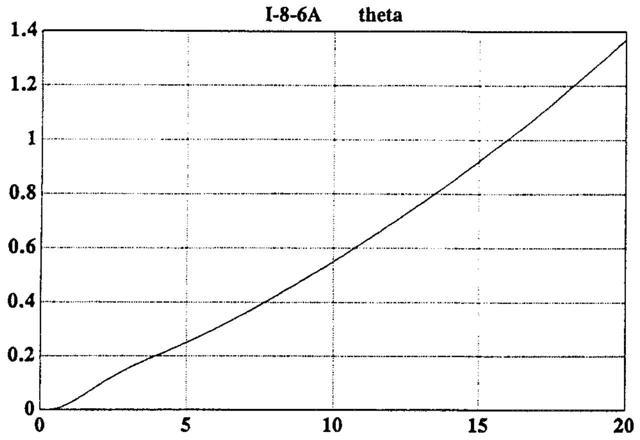

I-8-6A alpha rate
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20



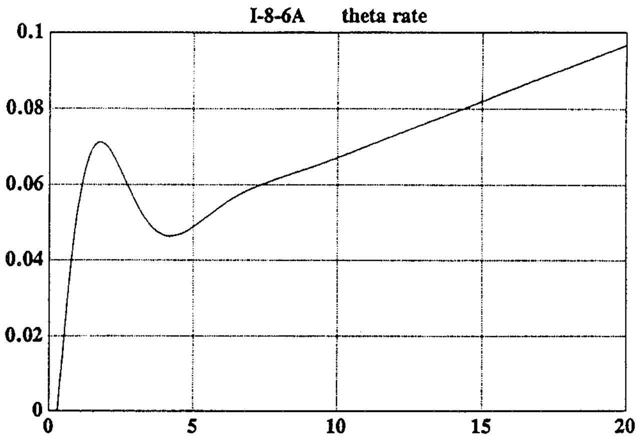
I-8-6A pitch rate



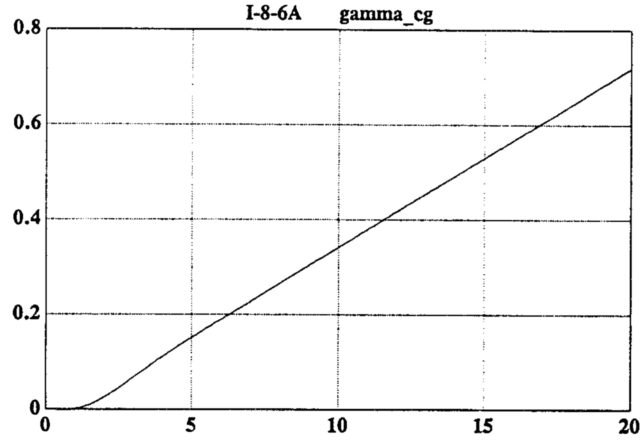
I-8-6A rate of pitch rate



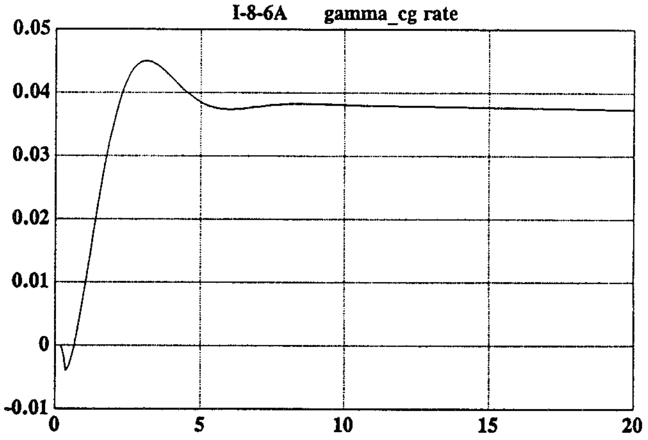
I-8-6A theta



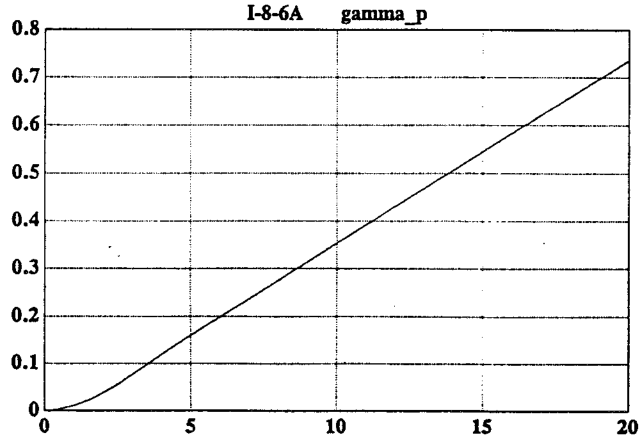
I-8-6A theta rate



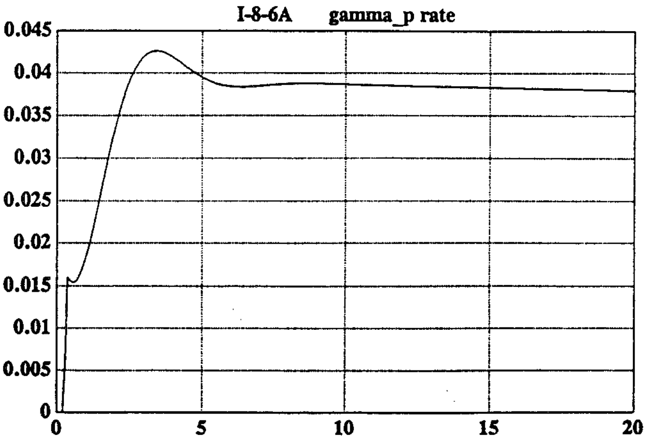
I-8-6A gamma_cg



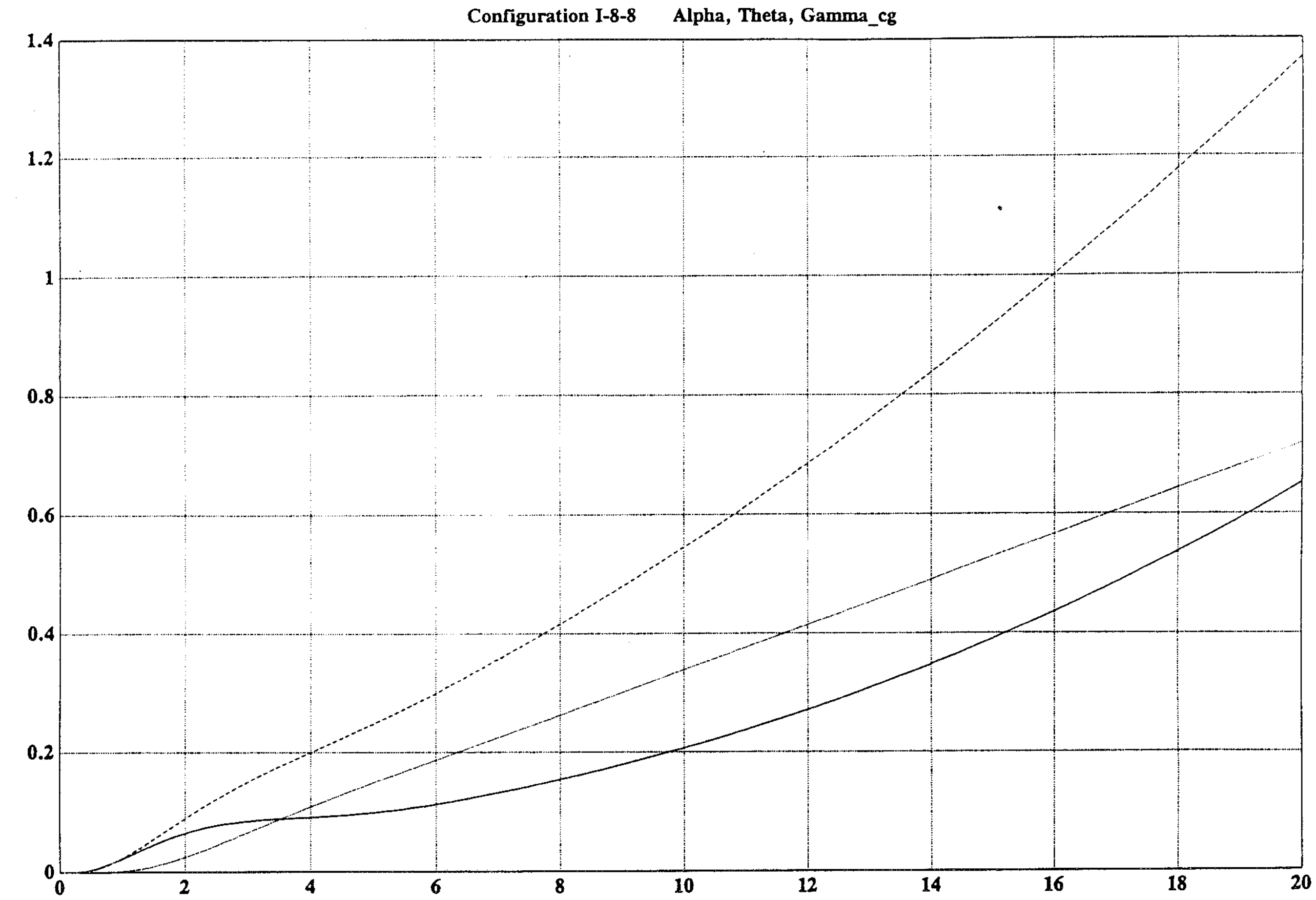
I-8-6A gamma_cg rate

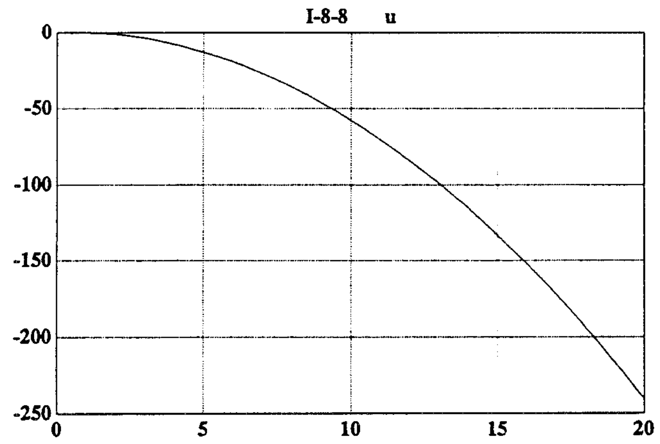


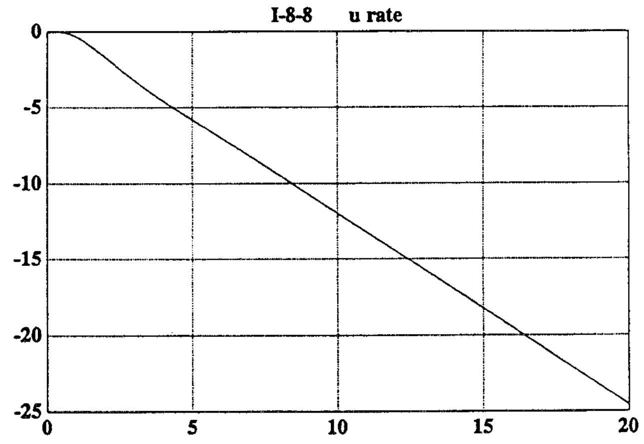
I-8-6A gamma_p

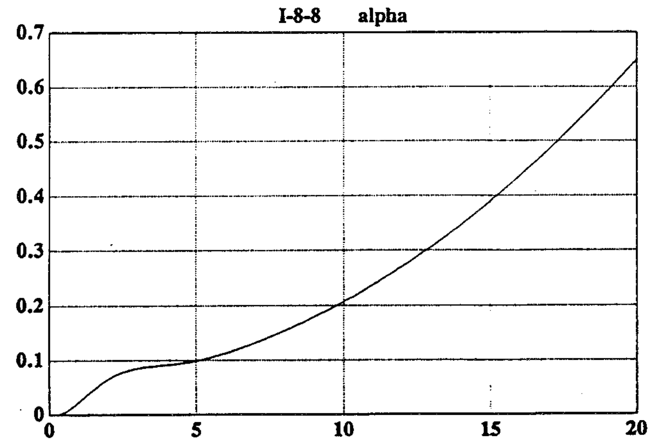


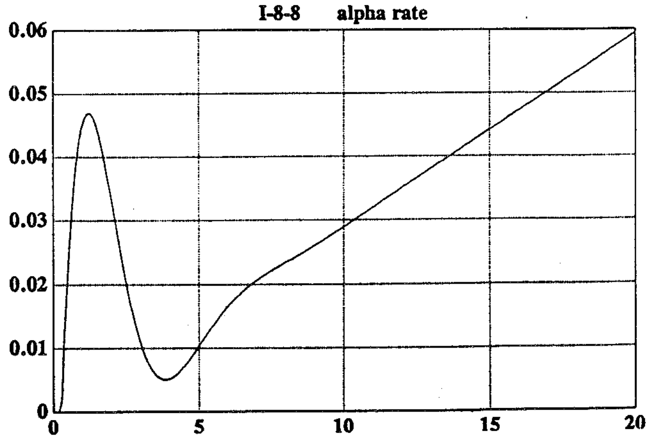
I-8-6A gamma_p rate

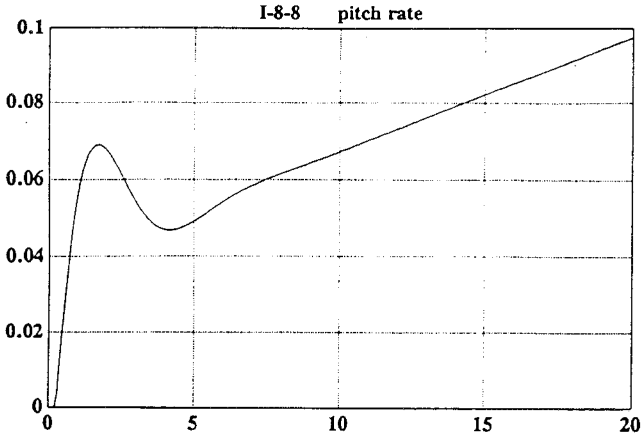

Configuration I-8-8 Alpha, Theta, Gamma_cg
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

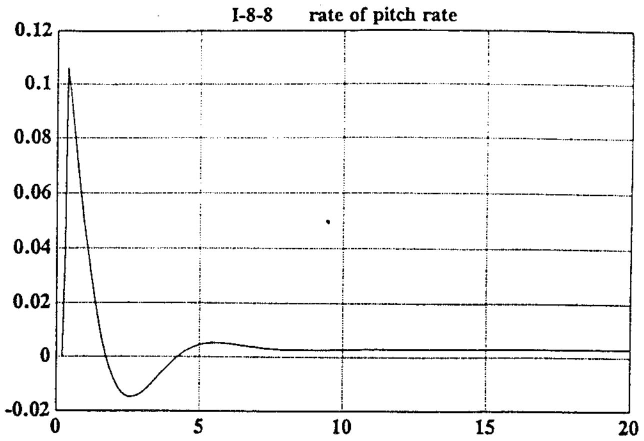

I-8-8 u
0
-50
-100
-150
-200
-250
0
5
10
15
20

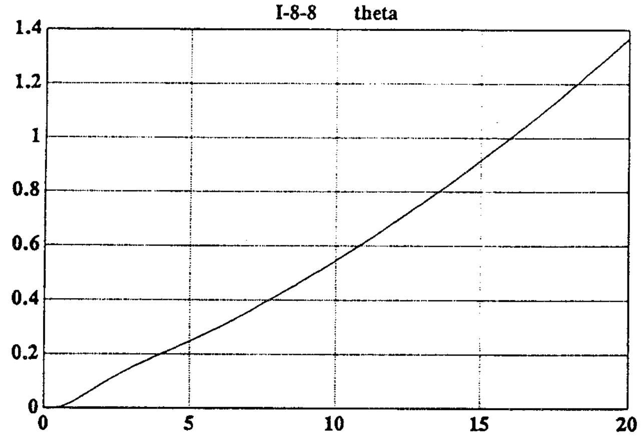

I-8-8 u rate
0
-5
-10
-15
-20
-25
0
5
10
15
20

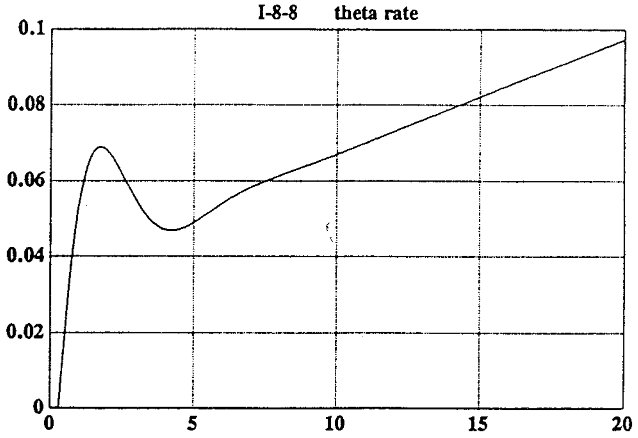

I-8-8 alpha
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

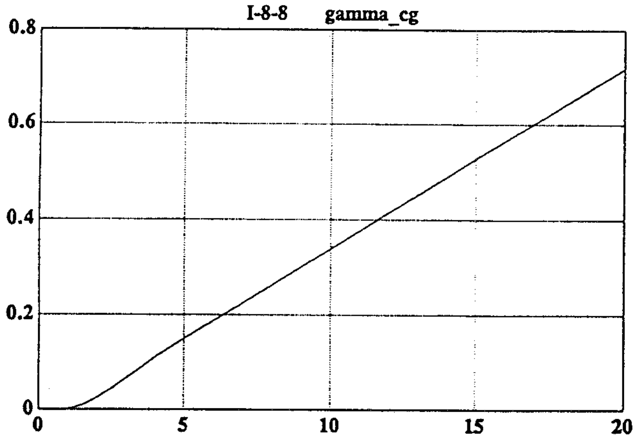

I-8-8 alpha rate
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

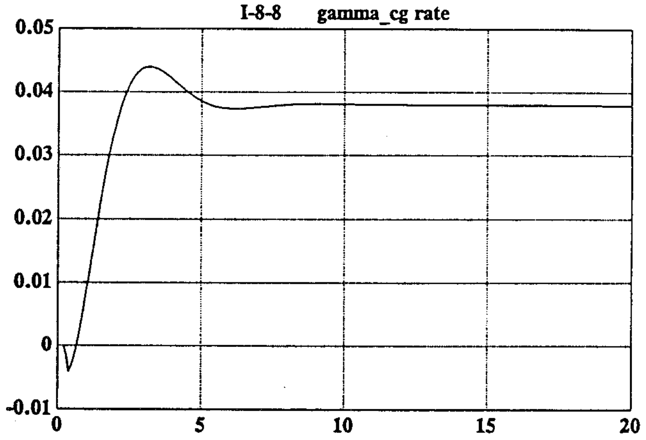

I-8-8 pitch rate

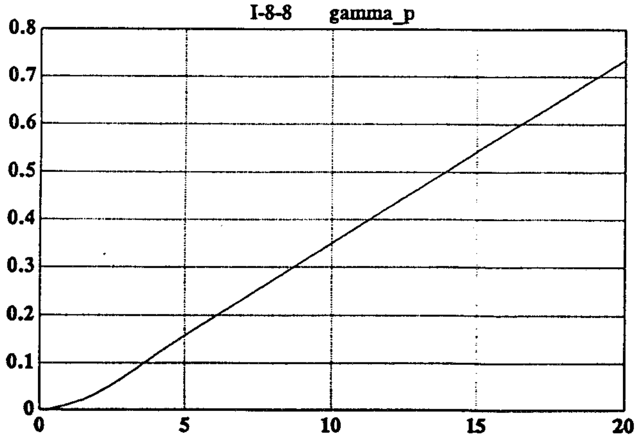

I-8-8 rate of pitch rate

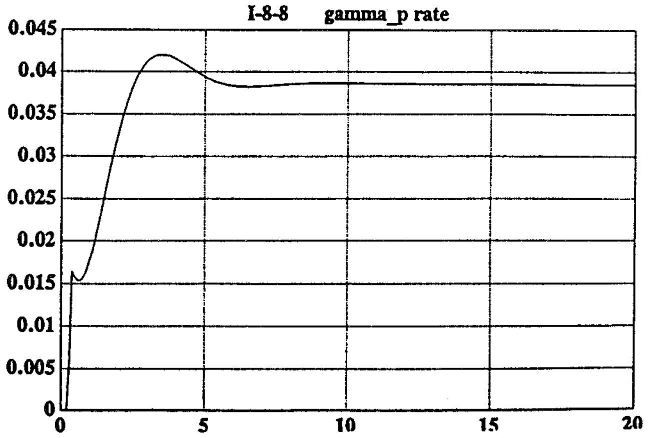

I-8-8 theta

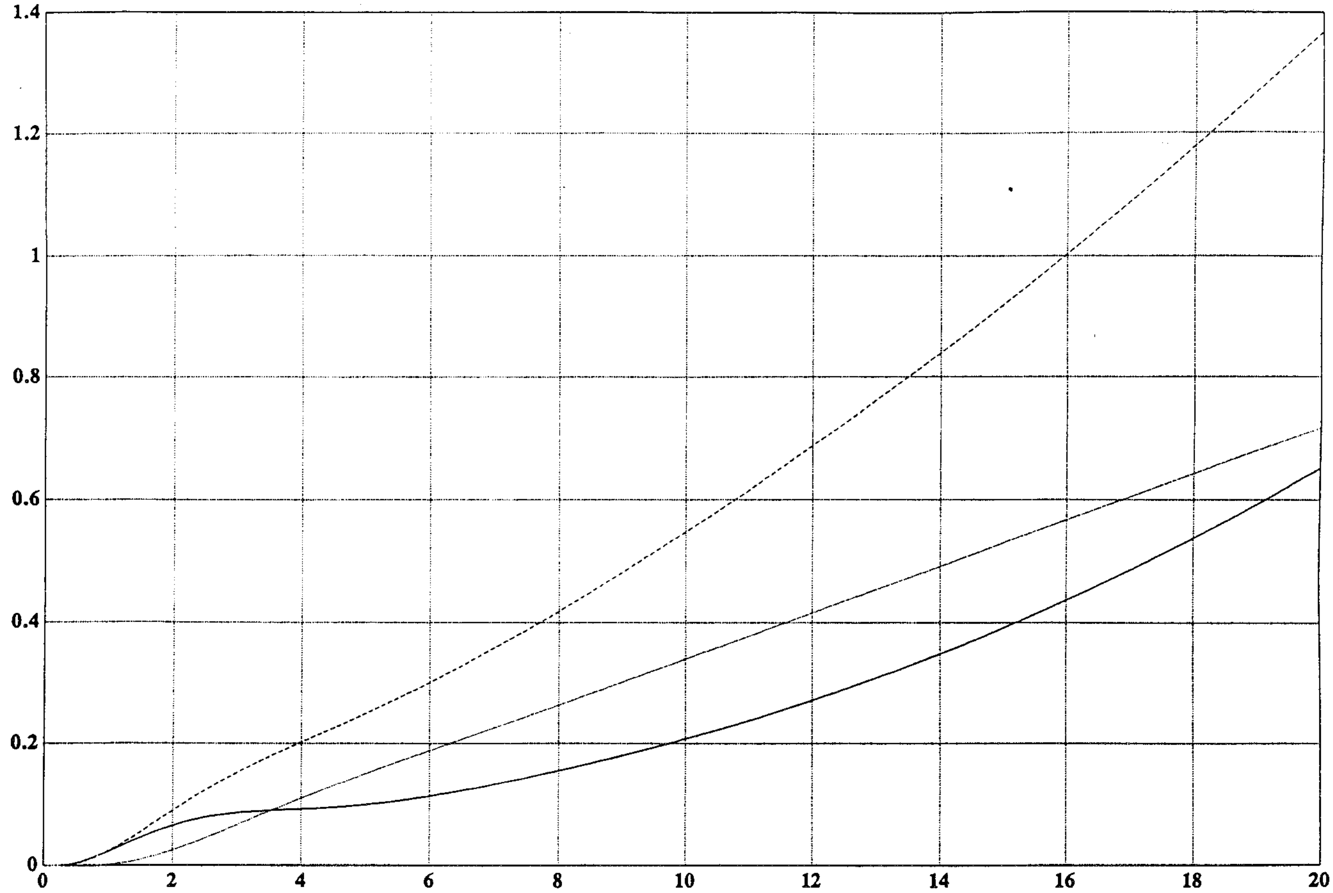

I-8-8 theta rate


I-8-8 gamma_cg

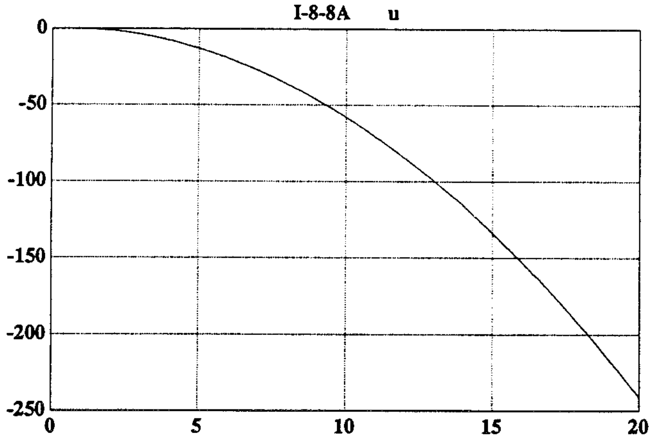

I-8-8 gamma_cg rate


I-8-8 gamma_p

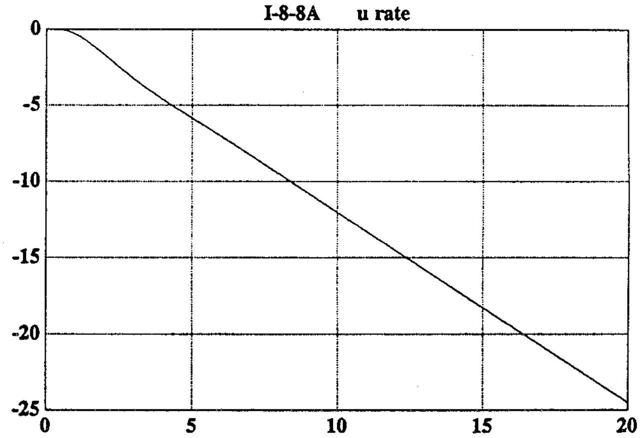

I-8-8 gamma_p rate



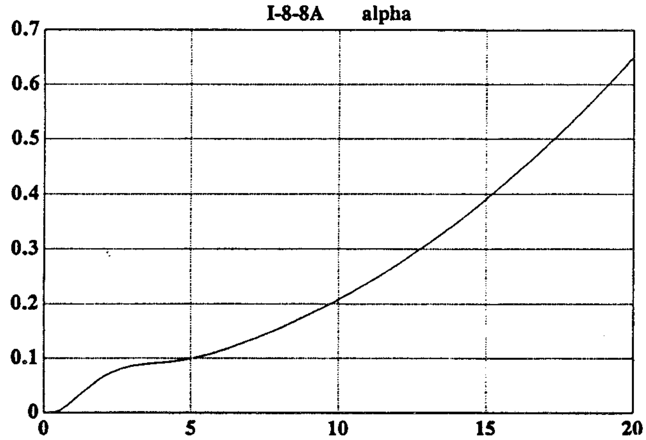
Configuration I-8-8A Alpha, Theta, Gamma_cg



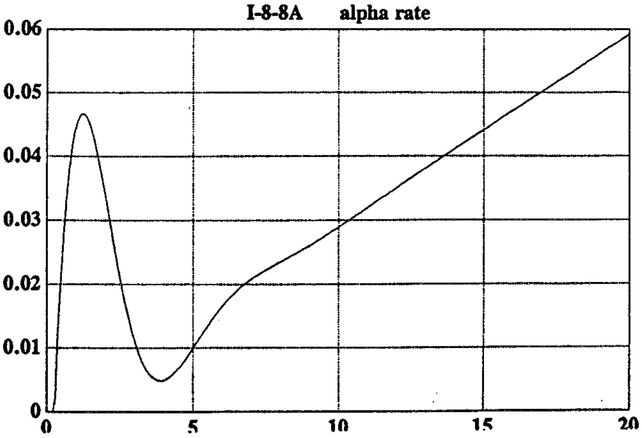
I-8-8A u



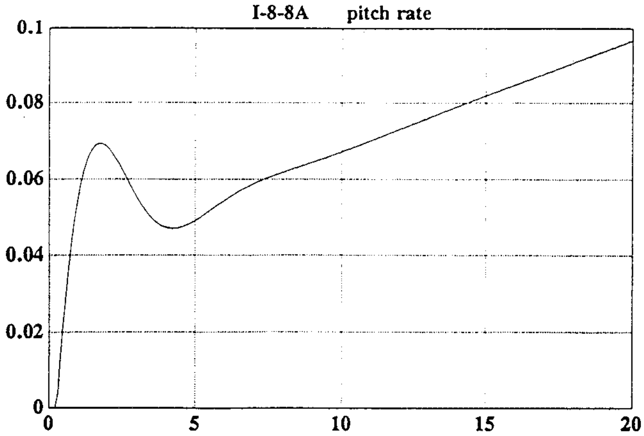
I-8-8A u rate

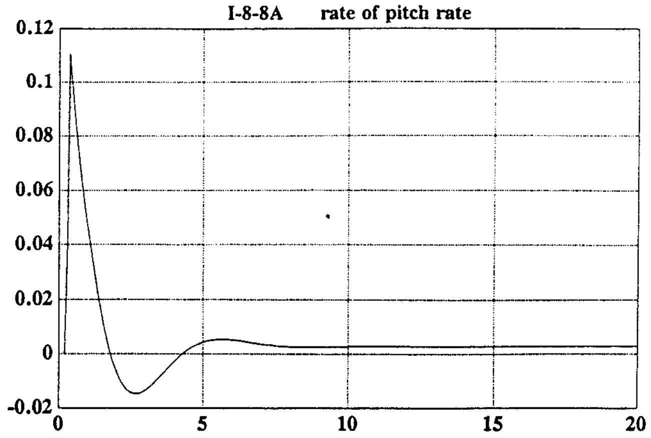


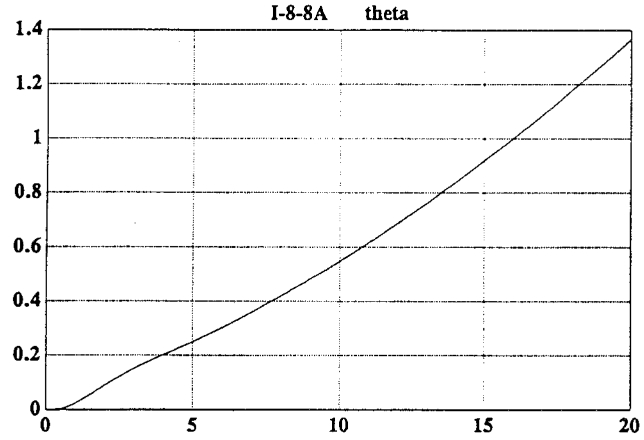
I-8-8A alpha

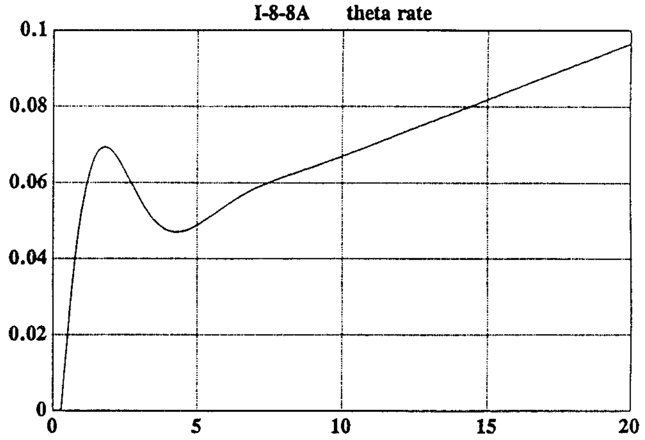


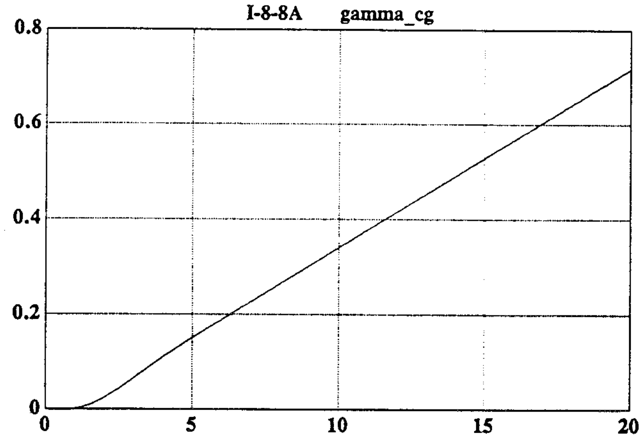
I-8-8A alpha rate

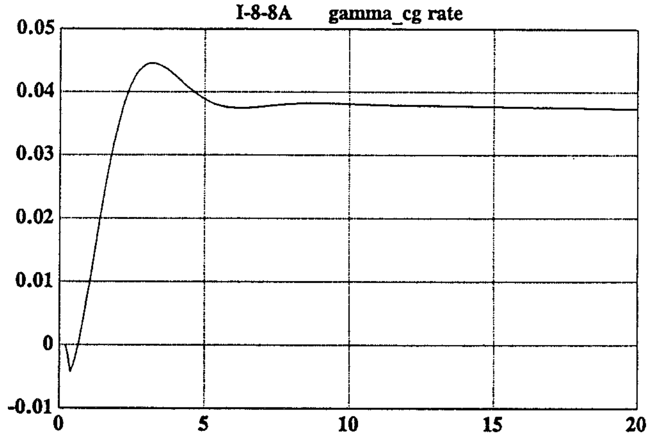

I-8-8A pitch rate
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

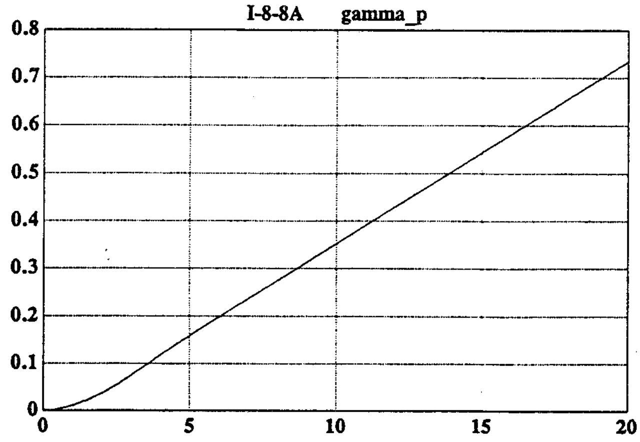

I-8-8A rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
5
10
15
20

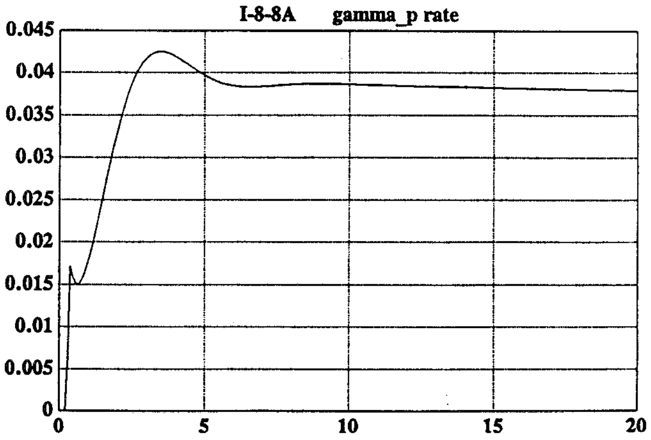

I-8-8A theta
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20

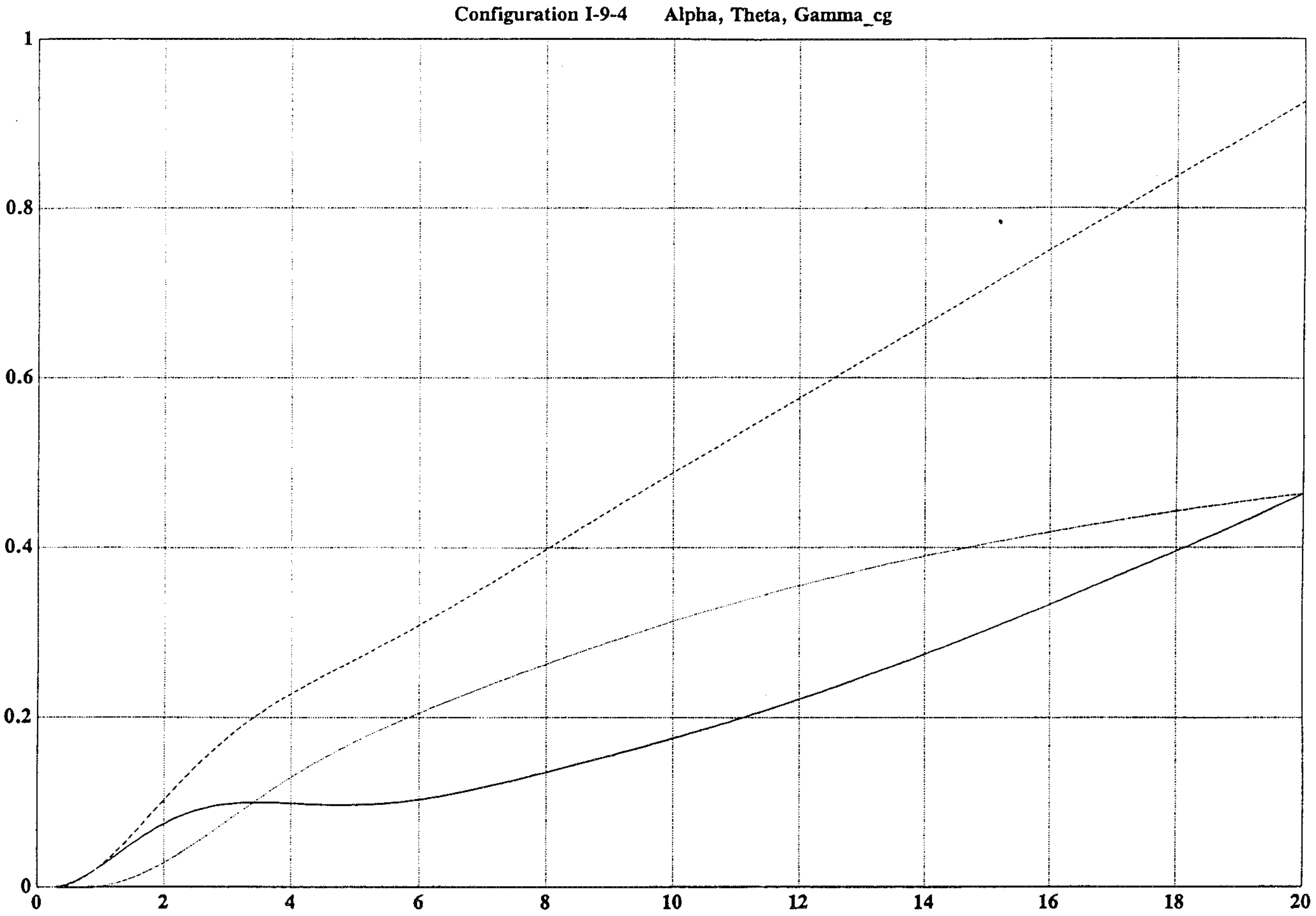

I-8-8A theta rate
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20

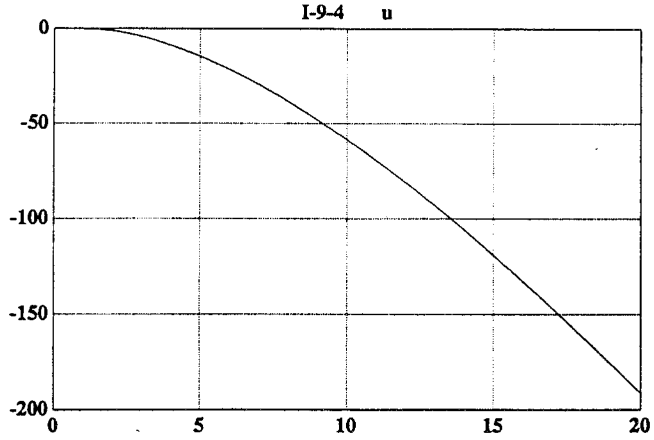

I-8-8A gamma_cg
0.8
0.6
0.4
0.2
0
0
5
10
15
20

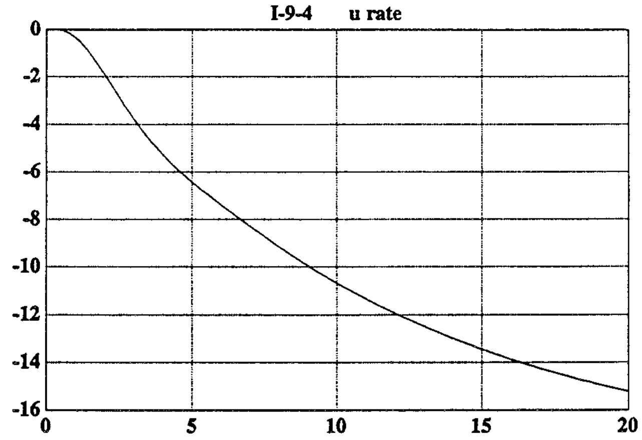

I-8-8A gamma_cg rate
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

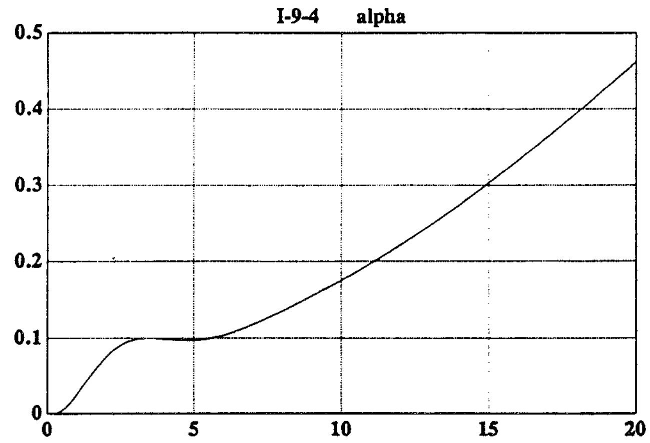

I-8-8A gamma_p
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

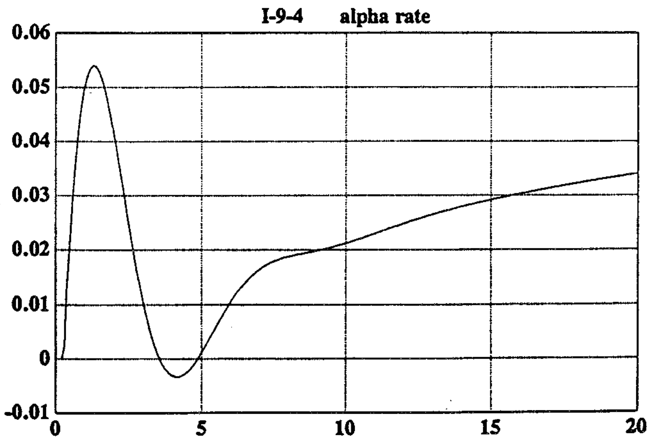

I-8-8A gamma_p rate
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20

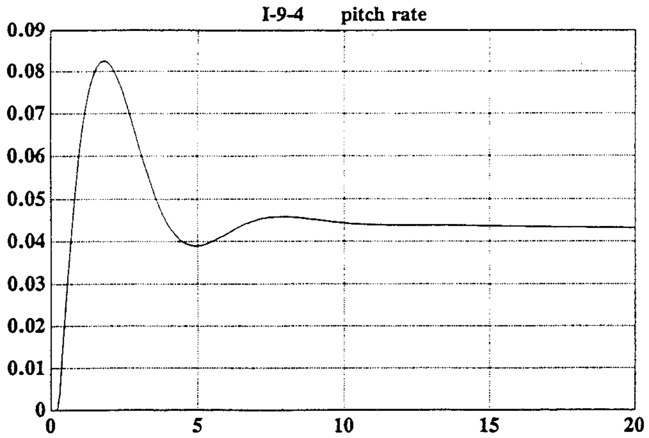

Configuration I-9-4 Alpha, Theta, Gamma_cg


I-9-4 u

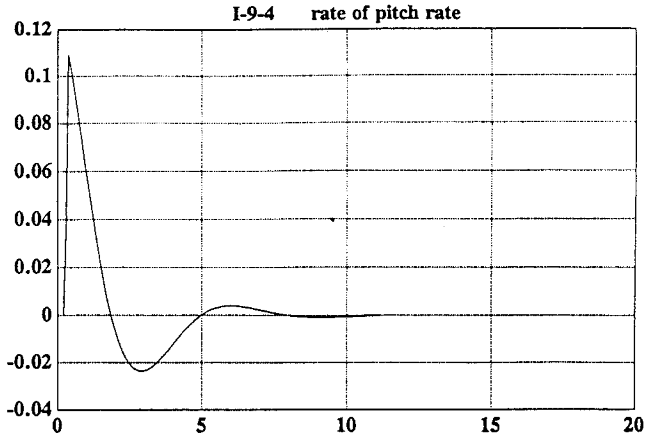

I-9-4 u rate


I-9-4 alpha

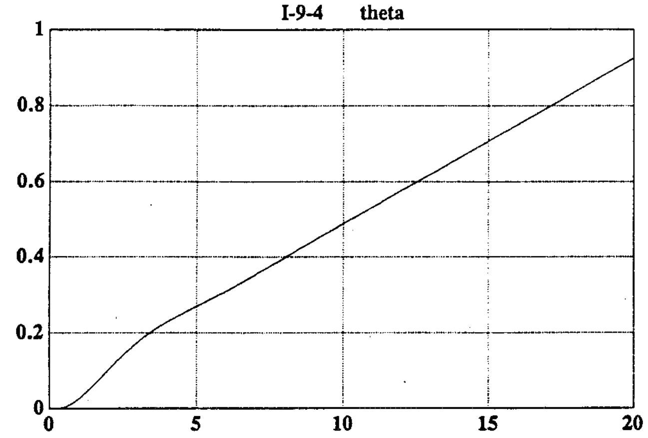

I-9-4 alpha rate



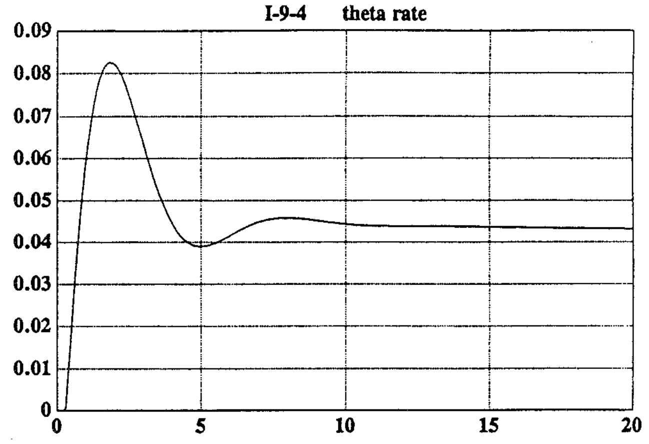
I-9-4 pitch rate



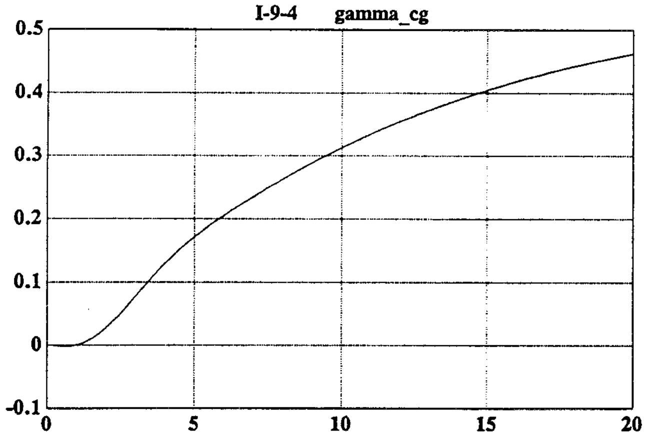
I-9-4 rate of pitch rate



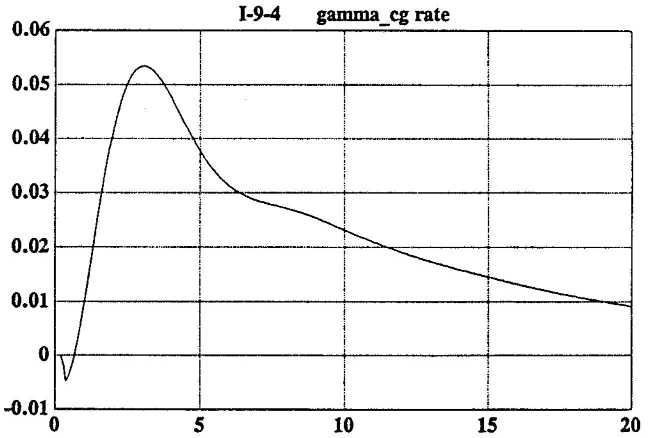
I-9-4 theta



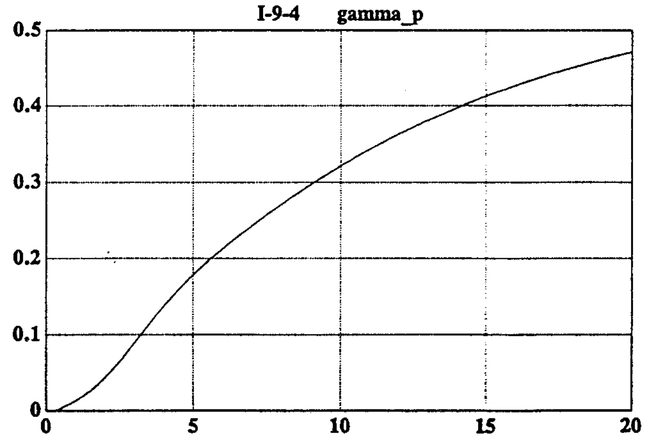
I-9-4 theta rate



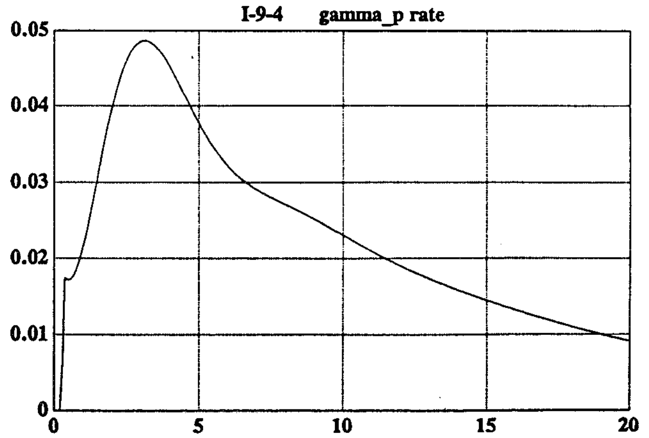
I-9-4 gamma_cg



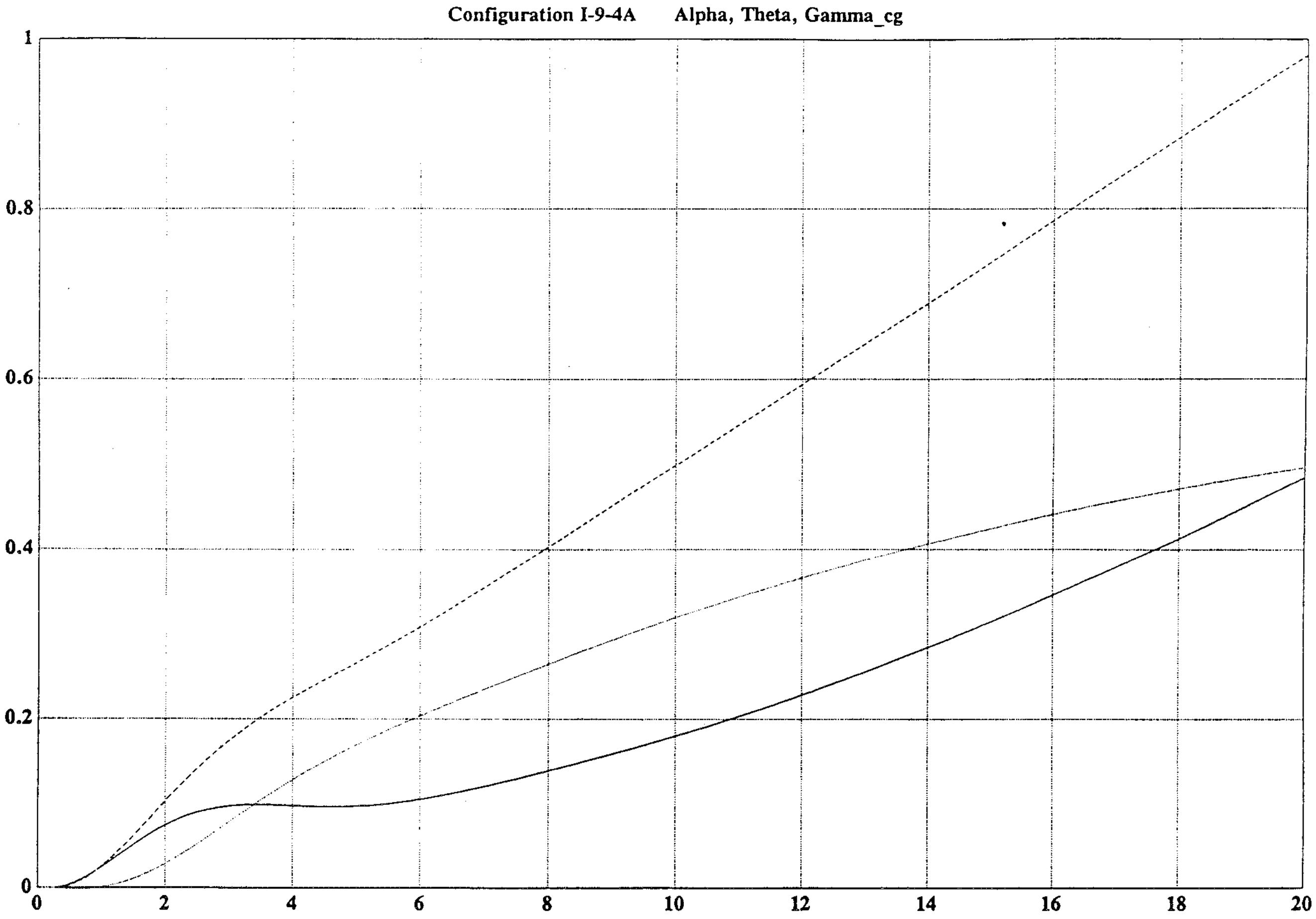
I-9-4 gamma_cg rate

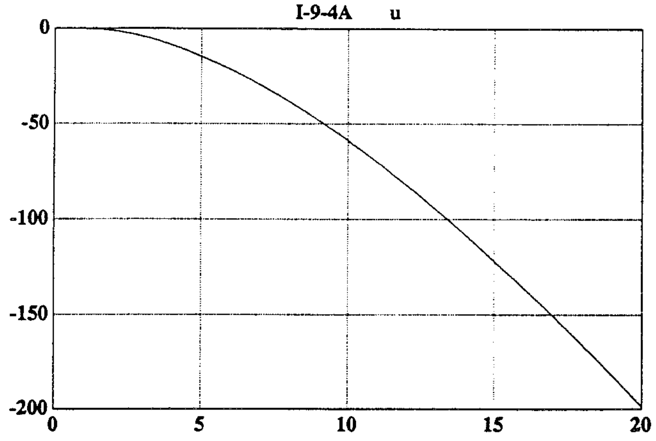


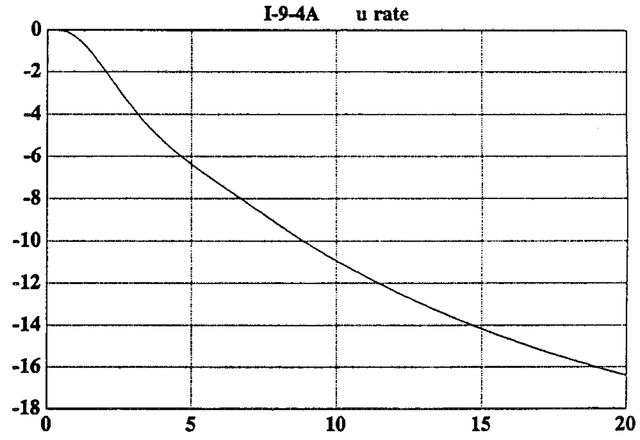
I-9-4 gamma_p

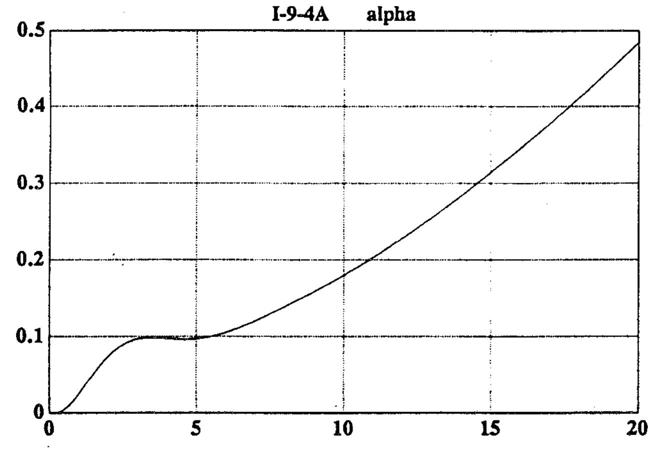


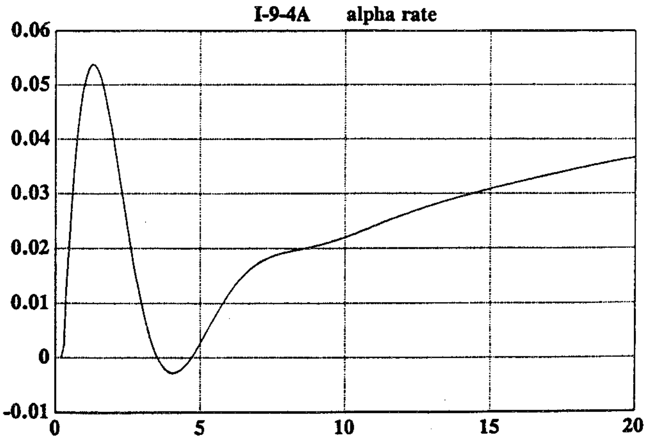
I-9-4 gamma_p rate

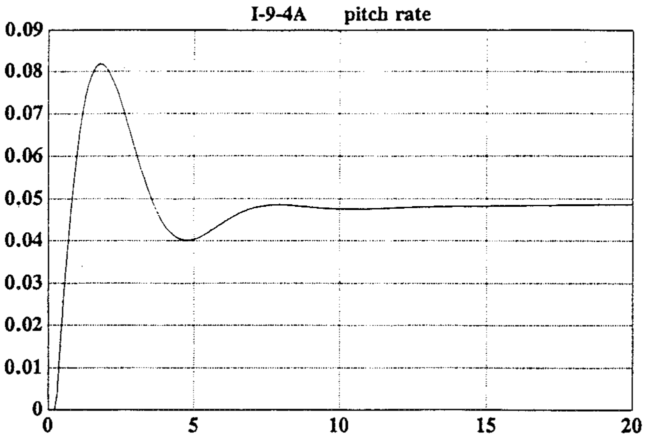

Configuration I-9-4A Alpha, Theta, Gamma_cg
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

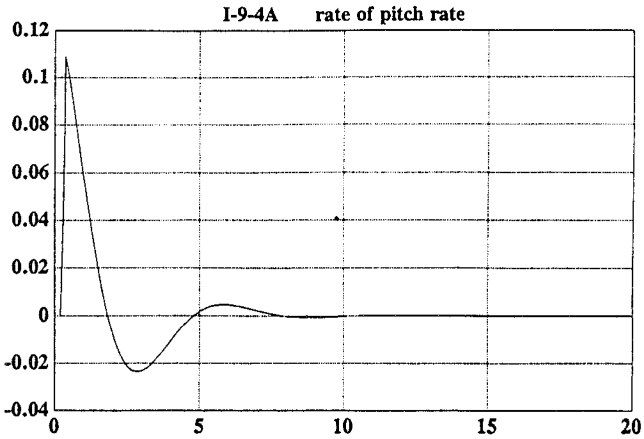

I-9-4A u
0
-50
-100
-150
-200
0
5
10
15
20

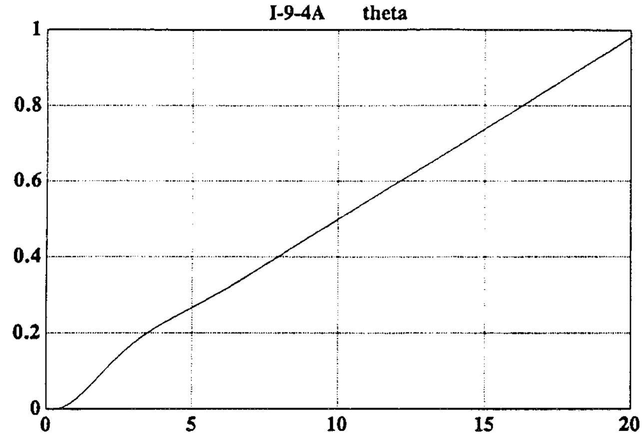

I-9-4A u rate
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
5
10
15
20

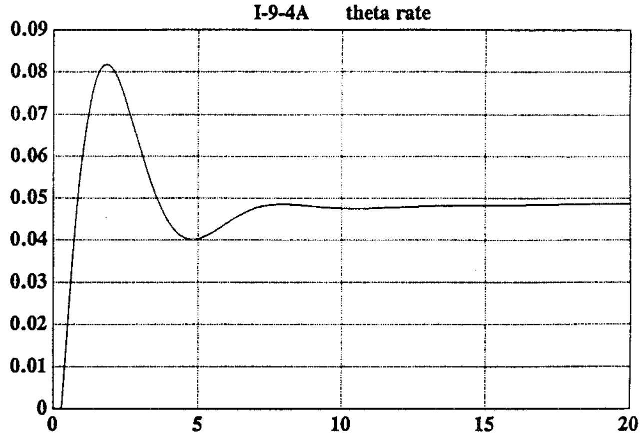

I-9-4A alpha
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

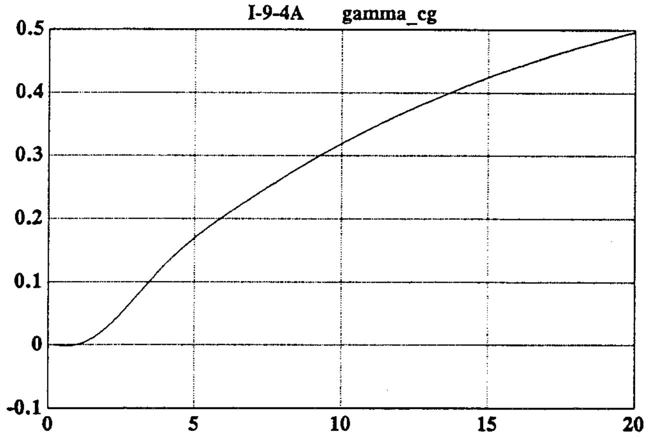

I-9-4A alpha rate
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20

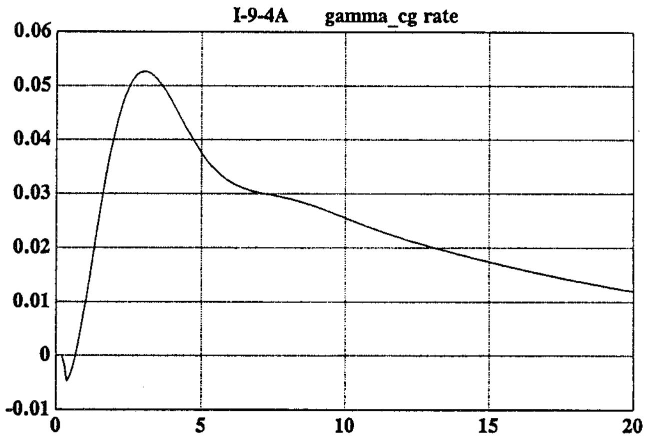

I-9-4A pitch rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20

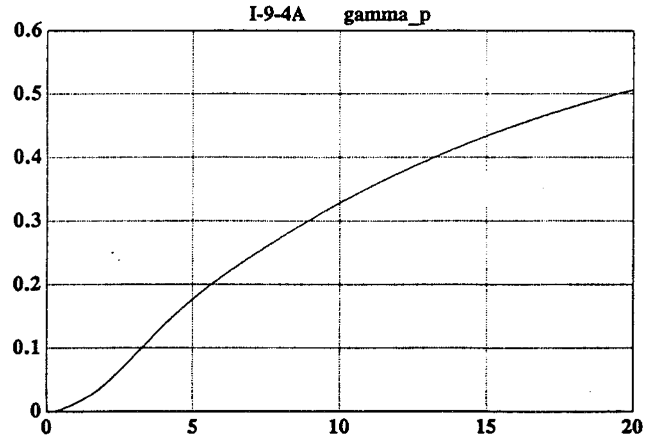

I-9-4A rate of pitch rate
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20

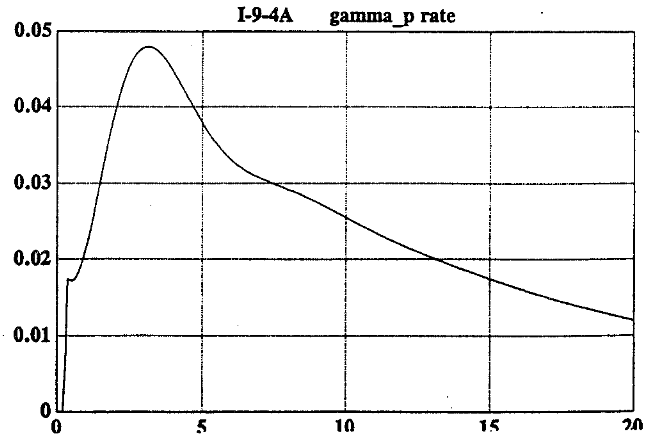

I-9-4A theta
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20


I-9-4A theta rate
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20


I-9-4A gamma_cg
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20


I-9-4A gamma_cg rate
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20


I-9-4A gamma_p
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20


I-9-4A gamma_p rate
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20