HANDLING QUALITIES FOR UNSTABLE COMBAT AIRCRAFT

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Abstract

Unstable aircraft depend completely on the flight control system to stabilise the response modes. The resulting pitch handling qualities differ significantly from the conventional. Current criteria may be impossible to apply and serious handling problems have been experienced in some recent aircraft. Handling qualities analysis methods are presented which allow previous data from any source to be directly applied to unstable aircraft control design and which ensure complete freedom from pilot induced oscillations. An example is given of the excellent handling qualities which can be achieved. The unconventional nature of the long period and attitude related responses are discussed.

1 Introduction

The most obvious handling qualities requirement for an unstable combat aircraft is that it should not appear so to the pilot. This primary aim can be achieved by the on-board sensing of inertial motion and airflow direction to provide stable response modes and piloted manoeuvre demand control. A common flight control system (FCS) for unstable aircraft is pitch rate manoeuvre demand with proportional plus integral feedforward of pitch rate error, which provides a good approximation to attitude hold, now known as "superaugmentation".

For fully carefree handling with protection from stall departure, overstressing and unrestricted control inputs, it is necessary to incorporate supplementary angle of attack and normal g demand paths, and these terms may also be used for extra augmentation outside the integral loop. It is possible to use these as primary demand modes, but although the handling can more nearly resemble the conventional in some respects they are likely to be less satisfactory than pitch rate demand. As damping augmentation is always necessary the latter has become the usual core around which the full FCS is built.

Good handling does not automatically result from use of manoeuvre demand control but must be designed in. Serious handling problems have occurred in some fly-by-wire aircraft as a result of high order system effects (1), but it has also proved difficult to translate the existing handling criteria into suitable forms. Theoretical studies of superaugmentation (2,3) show that the response characteristics differ both in kind and degree from the conventional and cannot be described by normal pitch modes.

New methods of identifying handling qualities (4,5) have been under development at Warton for a number of years. They were used in the design of the digital control laws for the FBW Jaguar (6) to give excellent handling in all critical flight phases, eg take off, landing, instrument approach, flight refuelling, formation flying, aerobatics, high speed low altitude flight in turbulence, air to air and air to ground tracking where median errors of 2 mils or less were regularly achieved. These qualities were maintained over a range of stabilities from normal Jaguar to highly unstable with only minor changes to the control laws. Identification of the high order causes of pilot induced oscillations enabled them to be excluded completely by specific control law design.

This paper discusses how a wealth of untapped handling qualities information can be identified and applied to superaugmented FCS design. Analysis by the new methods shows that far from being contradictory and inconsistent (1), the older data display a large measure of agreement. A completely detailed set of criteria is not offered in this paper because of lack of space. The intention is to encourage new approaches to the design of control laws which are exceptionally easy to apply, retain total visibility of all aspects of handling, and are highly effective in practice.

2 The Current Short Period Thumbprint

A great deal of handling qualities research was conducted in the 15 years prior to publication of the completely revised flying qualities requirements (7) in 1969. In the 1950's the variable stability B-26 and F-94 research aircraft operated by the Cornell Aeronautical Laboratories examined the influence of the short period frequency and damping. The results were presented in the "thumbprint" format of areas of handling qualities considered as best tested, good, fair, etc. (8,9, 10). Another thumbprint (11) resulted from a North American Aviation vertical motion simulator study of low altitude high speed pitch handling and riding qualities. Lack of agreement in the results led to further studies, eg (12-26).

Two related parameters became alternative candidates for inclusion into new criteria. These were T_{θ_2}, the attitude frequency response lead time constant, also called the flight path to attitude lag time constant, and n/α, the normal g per radian angle of attack. They are inversely proportional and connected by true speed, but have the different connotations of dynamic attitude response (T_{θ_2}) and static lift gain (n/α).

The derivation of the final choice has been described in (27). The short period requirement specifies maximum and minimum values of $\omega_{sp}^2/n/\alpha$ and damping ratio. The frequency values are directly equivalent to the initial pitching acceleration per steady g, the well known Control Anticipation Parameter intended to set limits on abrupt or sluggish attitude response. There is also a direct relationship to the manoeuvre margin, and so this format connects lift, attitude and stability parameters in a single requirement.

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The current requirements can be transformed back into a thumbprint, Figure 1, where the four examples are plotted. The agreement between them is not good. It was acknowledged (27) that the Level 1 upper boundary was not supported by much data, and there has been almost universal agreement in subsequent experiments, eg (28,29), that it is set too high. The lower boundary is more problematical because it can be shown to be both too low and too high, a conclusion in agreement with Warton experience over the years.

3 Equivalent Response Pitch Handling Qualities

A number of individual handling characteristics can be observed in a pitch short period time response. They are shown graphically in Figure 2 and comprise (neglecting tail load effects):

- Initial pitch acceleration/g (CAP)	deg/sec^2/g
- Time at pitch acceleration peak	$t_{\dot{q}}$ sec
- Ratio of peak to steady pitch rate	q_m/q
- Time at pitch rate peak	t_q sec
- Effective time delay of pitch rate	t_d sec
- Pitch attitude dropback/overshoot	DB/q sec
- Flight path angle delay	t_γ sec
- Response time to steady g	sec
- Response time to steady pitch rate	sec

Two of these, $t_{\dot{q}}$ and t_d, are essentially high order parameters. Although they are inevitably present in any low order aircraft which uses power controls, they will be negligible in effect. All the rest are related to some or all of ω_{sp}, ζ_{sp} and T_{θ_2} which uniquely define them for a given low order configuration. In a high order system, including superaugmentation, they will be present but not in a unique relationship. They are easy to measure from such a response calculation and as they can be related to particular handling attributes they contribute to a very detailed picture of the overall handling qualities. They can be considered to be "equivalent response parameters".

Figure 3 shows the relationship between flight path angle and attitude paramters. The FCS designer has no control over the value of T_{θ_2} because it is a function of the aerodynamic and mass configuration, unless direct lift augmentation is used. A faster response in flight path is obtained only at the expense of a more abrupt attitude response with greater dropback and pitch rate overshoot, or bobble. This is the result of increasing the short period frequency, which moves the flight path and attitude curves leftwards by the same amount, though of course they must continue to originate at time zero. Decreasing the frequency drags them out to the right, with increasingly sluggish attitude overshoot and a slow flight path response. The frequencies and dampings at which these excesses in attitude behaviour occur depend on T_{θ_2}.

The examples in Figure 2 have the same frequency, damping, n/α, initial pitch acceleration per g and flight path time delay, and are at the lower limit of the Level 1 boundary. Their pitch responses exhibit large attitude dropback, zero dropback or large attitude overshoot associated with the wide range of wing loadings and airspeed representing greatly different types of aircraft. Although the flight path time responses are the same, they do not follow the same flight path. The delay of one second represents distances proportional to the speed of about 250, 500 and 1000 feet before the change in flight path angle rate is effectively established. These responses are totally different in character and two of them have unsatisfactory features, yet by the usual criteria all qualify identically as satisfactory.

4 The New Short Period Thumbprint

An exceptionally detailed picture of the pitch attitude and flight path response can be obtained in the format of Figure 4 by the addition of constant response lines. The solid lines are functions of $\omega_{sp}T_{\theta_2}$ and ζ_{sp} and are common for all T_{θ_2}. The dashed lines are also functions of T_{θ_2} and while the contours remain the same the values associated with them are directly proportional to T_{θ_2}. Here they are shown for $T_{\theta_2} = 1.0$ but they can be scaled proportionately for any other. It is not possible to construct a unique thumbprint, as each value of lift parameter needs a different one.

A closed contour of handling qualities will be bounded by lines of pitch rate overshoot, time at peak pitch rate, attitude dropback or overshoot and flight path time delay. The PIO tendency line (14) is a somewhat controversial feature of these early experiments in that it represents impossible aerodynamics in an unaugmented aircraft, with pitch and angle of attack rate damping equal in magnitude but of opposite sign. Because it was actually achieved by augmentation it is half way to modern high order problems (5) but these are much more complex and involve additional parameters which are not present here.

Pitch acceleration can be indicated on a CAP scale which depends on n/α. Its validity is open to doubt because it is the first low order characteristic to suffer distortion as the short period frequency is increased by a flight control feedback and actuation system (8,18), rather than by natural aerodynamic stiffness effects. Pitch rate overshoot was shown to remain well matched up to quite high frequency (18) and recent studies show that the time at peak pitch rate, attitude dropback and flight path delay are also modelled reasonably accurately in such experiments.

The complete thumbprints from the Figure 1 examples are plotted in Figures 5 to 8. To these Figure 9 is added showing the results of another variable stability flight experiment (23). While it would need the study of many more sets than these to arrive at formal requirements, much of great interest is revealed in a T_{θ_2} spectrum ranging from 2.0 to 0.31.

- Study of the parameters in the different figures shows the wide variation in their relationships as T_{θ_2} changes.

- The most satisfactory handling areas are in the upper part of the figure for large T_{θ_2} and move towards the lower part as T_{θ_2} reduces. This follows a trend of constant time at peak pitch rate.

- The lefthand ends of the thumbprints are clearly influenced by low short period damping irrespective of T_{θ_2}. This handling area is not of great interest for superaugmented FCS because the response is usually well damped. The amount of pitch rate overshoot bears little relationship to any particular damping value.

- The lower righthand ends of the thumbprints tend to follow a line of time at peak pitch rate into a region of low pitch attitude overshoot and moderate flight path time delay, parallel to the zero dropback line. A cut-off at a specific upper damping level does not seem appropriate.

- Poor handling can occur near the PIO line, and serious in-flight PIO has been reported even from points below it which have reasonable damping. The associated nonlinear pilot behaviour has been studied previously (13, 5).

Other factors play a part. In the repeat of the B-26 experiment (31) some years later the boundary of Level 1 handling (pilot rating of 3.5 marked by the line of crosses in Figure 5), includes areas originally rated as poor. Changes in the aims and method of evaluation in the intervening years resulted in a more tolerant pilot opinion. The actual task can alter the rating by several points, as shown in later Calspan flight experiments (28).

The effect of the stick can be significant. These equivalent responses are based on a pitch control step input which will never be applied in practice, but it defines a consistent standard for the dynamics of a response without the need for a possibly contentious choice of a pilot input model. The stick characteristics act as a filter between the pilot's intentions and his actions. The B-26 had large stick forces and displacements per g by fighter standards, softening the effects of abrupt pitch behaviour, increasing any sluggish tendencies, and therefore almost certainly biassing the preferred configurations upwards in Figure 5. Experience with sidesticks of limited or zero travel have indicated a preference for slower responses appropriate to the absence of a significant filtering effect.

The carrier approach and landing experiment (23) was obviously oriented completely to a single task. The results in Figure 9 show excellent rating in a region where satisfactory values of flight path time delay, a crucial parameter for this task, can only be achieved with substantial attitude dropback and pitch rate overshoot. The handling is not adversely affected by the latter provided they do not occur too rapidly or too slowly. The larger stick forces and displacements usually found in the landing configuration are favourable in this respect.

The need for awareness of the experimental circumstances when drawing conclusions is exemplified in the results of the LAHS vertical motion simulation (11) shown in Figure 8. The high maximum short period frequency of 2 cps would not cause exceptional attitude responses, the dropback being small and the pitch rate unobtrusive in most of the region. As attitude was presented to the pilot only on a head down all-attitude indicator, it could have had little influence on the ratings. The main CRT tracking display presented terrain height, height error and instantaneous rate of climb. The latter, equivalent to a flight path angle display, provided the principal dynamic tracking information. Pilot rating and the PIO boundaries were therefore based on flight path control with little or no attitude content. They actually correlate very well with the high order attitude PIO criteria discussed below if considered as equivalent to an experiment with attitude dynamics to which a 0.31 second lag has been added. The low order attitude dynamics alone, even those below the nominal "PIO" line, are not particularly prone to PIO for this value of T_{θ_2}.

It will be clear that despite the depth of information within it a thumbprint is not a useful general format because it is not unique for all T_{θ_2} values. In the design of a superaugmented FCS, this is not a disadvantage because the normal low order relationships do not exist. The best values of the equivalent responses can be built into the control laws, individually selected with respect to the flight task. The results shown above are already sufficient to indicate some pointers to the satisfactory values.

5 Analysis of Low and High Order Handling

The equivalent response parameters can be obtained from the handling investigations listed or in any other source. If the value of T_{θ_2} is not quoted it is usually easy to estimate. The appropriate transfer functions can then be constructed and an actual time response calculated for direct measurement of the parameters, or if the model is sufficiently low in order they can be derived by the use of simple formulae and graphical plots. It is also possible to construct background carpets of equivalent response parameters on any of the formats used for presenting the low order results in these references, or the data points can be transferred to the thumbprint format as was done in Figure 9.

If the responses are from a high order example, there is no alternative to the construction of the transfer functions. The best known examples are the variable stability Calspan NT-33 flight experiments (28,29). These were low order models made high order by the addition of simple stick filters. Despite this simplicity, the essential elements of high order handling problems were clearly revealed for the first time. They also introduced the situation in which the response to external forcing such as gusts was not necessarily similar to the response to pilot demands. The results show that the basic handling is rated according to the same equivalent response characteristics as any low order example, and that the high order features leading to PIO problems can be identified separately. In all of this they were directly relevant to the short period handling qualities of superaugmented aircraft.

5.1 Low Order Characteristics

Only the briefest summary of the results of such analyses can be given in this short paper. Because they are aimed at providing handling criteria for well-damped superaugmented aircraft, low damping cases are not considered.

- Handling will be unsatisfactory near the upper Level 1 frequency limit as a result of pitch rate and attitude bobble effects, though flight path control will be excellent.

- Handling near the lower Level 1 frequency limit may be unsatisfactory for tasks requiring precise flight path control such as landing or flight refuelling, but can be near optimum for attitude control.

- For compensatory target tracking, near zero dropback is best, resembling the optimum K/S identified in pilot-vehicle systems analysis (12) and earning the rating comment "The nose follows the stick". Some dropback can be considered satisfactory but the amount varies with the pitch rate overshoot amplitude and rapidity.

- Large attitude overshoot causes "digging in", unpredictable response and overdriving. Small amounts may be satisfactory for routine attitude control or for compensatory tracking with limited travel sticks.

- For attitude to be controlled predictably it must reach steady conditions within about 2 seconds.

- The K/S response is not needed for the precision tasks of landing and flight refuelling and is secondary to good flight path response.

- Very abrupt responses cannot be made satisfactory by increasing the stick force and displacement per g.

- An increase in system order by the use of stick filters need not introduce high order handling characteristics. Such filters can greatly alter the CAP with little corresponding effect on handling.

5.1.1 Analysis Examples

Variations on two flight conditions are shown as examples. These are Case 8 from the fighter handling qualities experiment (28) in Figure 10 and Case 1 from the LAHOS landing approach experiment in Figure 11 (29).

8A was set at the Cat.A Level 1 upper frequency. Control of g was very good but the rating was a 6 because of small but severe bobble or pitch oscillation, particularly in tracking with small stick inputs. This was referred to as PIO. The effects were worse when correcting for the effects of turbulence. The attitude dropback was of moderate amplitude but it was rendered step-like by very large and rapid pitch rate overshoot.

8B with a 0.052 second lag filter earned a 3 without a target aircraft but a 7 with one. Control of flight path was excellent. CAP was halved and the dropback slightly reduced, but the pitch rate overshoot was still large and rapid. The good damping permitted reasonable tracking of a stationary target but there was continuous bobble against an aircraft target.

8D with a 0.3 second filter earned a 2 with a target aircraft, with low CAP, zero dropback and and small and not too rapid pitch rate overshoot. Control of flight path was good. The rating was now little affected by turbulence even though this forcing was unchanged. Despite the large added lag, high order effects on the pitch rate delay and pitch acceleration peak time were negligible.

1-1 was set near the Cat.C Level 1 lower frequency limit. Although there was no major handling difficulty it was rated only 4. The nominal dropback is easily calculated as -0.08, but the response is so slow that a realistic value of -0.7, a very large overshoot, is obtained graphically from the first few seconds most relevant to the landing flare. Similarly the flight path time delay is an apparent 1.7 seconds though the nominal is 1.48. The pitch rate overshoot is low but takes about 2 seconds to peak and 5 to 6 seconds to reach a steady value. The aircraft had to be overdriven for tight control, which was referred to as a slight PIO tendency.

1-A was an attempt to quicken the response with a lead-lag filter to increase the CAP, but there was no change in pilot rating. The small filter time constants merely resulted in a sharp pitch acceleration spike. The reduction in attitude overshoot to a still large -0.4 and flight path delay to 1.4 seconds did not compensate for the almost unchanged time to peak pitch rate and the overall settling time.

1-3 has a lag filter of 0.25 second time constant, but far from improving the handling as a larger lag did for Case 8A, the effect was catastrophic. Approach handling was sluggish and delayed with a rating of 6. Landing was rated 9 and 10 with almost unavoidable PIO, one also occurring in a take off. High order effects are seen in the pitch rate time delay of under 200 m.secs and the 0.55 seconds to reach the pitch acceleration peak.

5.2 High Order Characteristics

These are primarily associated with pilot-vehicle closed loop handling problems or PIO. As this term has been used to describe low order problems, the differences should be clearly understood. The abrupt pitch bobble type is discontinuous, consisting of repeated tracking corrections. The sluggish pitch overdriving type is also discontinuous with input pulses to stop the unpredictable excess in response. Although the aircraft is not under complete control it is not out of control.

High order PIO is a continuous out of control attitude instability, the amplitude ranging from small to large and potentially destructive. The common feature in the time responses of PIO configurations is a large delay in the time at the pitch acceleration peak, values larger than about 0.3 seconds indicating increasingly serious problems. There will also be an effective delay in the pitch rate onset but the correlation with PIO is poor. Because the problem is due to inadequate pilot-vehicle closed loop gain and phase margins, examination of the pitch attitude frequency response identifies the cause and the solution.

Figure 12 shows the features which separate low and high order pitch handling. The area of interest can be confined to the region of phase lags between 180 and 200 degrees which determines the PIO frequency. This arises from the success of the "synchronous pilot" (14) in PIO analysis, assuming that any pre-PIO equalisation is abandoned for a pure gain behaviour in the undamped or divergent oscillation. The correct frequency is adopted instantaneously with the stick in phase with the pitch attitude error and 180 degrees out of phase with the attitude. The stick is not always moved so purely in practice, but very often the pilot can be seen to apply the stick a little too quickly and then hold it while waiting for the pitch rate reversal before also reversing the stick.

The tendency of a configuration to PIO can therefore be assessed without using a pilot model by empirically establishing the range of characteristics found in actual PIO examples. Enough have now been published to do this with considerable accuracy. An important feature at the PIO frequency is the response gain. If this is small enough, dangerous oscillation amplitudes cannot occur, and PIO has not been found where this is less than 0.1 degrees per pound of stick force. This is not a completely necessary condition but it is a highly desirable design aim.

PIO's have occurred most frequently, though not exclusively, in the landing flare. The connection with the commonplace stick pumping is well established (4,5). This subconscious excitation of pitch acceleration in the flare occurs near the same frequency as a PIO. If the attitude in the oscillation suddenly intrudes into the pilot's awareness, a ready-made PIO is already in existence. The lower the frequency, the larger is the attitude oscillation at the usual acceleration amplitude of about 6 deg/sec^2, and the more likely the conversion becomes. This indicates strongly the desirability of a high crossover frequency through the PIO region.

While an oscillation amplitude of less than 0.5 degree in the flare will not usually be noticed, and one significantly more than a degree is very likely to, this or the corresponding pumping/PIO frequency is not an ideal parameter for correlation. The most successful has proved to be the rate at which the pitch attitude phase lag increases with frequency in the PIO lag crossover region, equally applicable to the landing or to target tracking tasks. By the nature of the attitude frequency response, if the crossover frequency is low and the attitude attenuates only slowly towards the crossover region the phase rate is large. If the frequency is high and there is substantial attenuation the phase rate is low. The gain margin is increased, the stick pumping amplitude is reduced and the tendency to PIO is decreased automatically by designing a low phase rate into the control laws.

This simple attitude parameter alone is almost sufficient to quantify the tendency to high order PIO, and it correlates well with available examples of high order PIO. Figure 13 shows the trends, replacing a previously published criterion (5). The accuracy is good enough to allow Level 1, 2 and 3 boundaries to be drawn if desired. For the control law designer it is enough to aim for a phase rate of less than 100 degrees per cps and attitude response smaller than 0.1 deg/lb at the crossover. These characteristics are a natural feature of low order aircraft whose attitude phase lag exceeds 180 degrees due to the power control and so could in principle suffer from PIO, yet do not. Early examples of bobweight PIO, eg (14), were high order in kind and are found to have had very large phase rates with the stick free.

For most combat aircraft configurations, consideration of normal acceleration effects does not improve the PIO analysis. The g at the cockpit is usually attenuated and phase advanced relative to the CG and will often not reach the 180 degrees lag necessary for piloted instability. Human sensing of the g response is poor (5) and at the initiation of the PIO the g may be undetectable. In large aircraft with the cockpit far ahead of the CG, the heave can have a significant effect and has to be taken into account in the dominant requirement to optimise the pitch attitude behaviour.

Although the attitude to stick force response gain is significant in PIO, there is little evidence that a damper modifies the pilot's stick phasing in a PIO and only the stiffness component should be used. Where PIO tendencies exist, they will be exacerbated by a high stick stiffness. Gradients of 5 to 8 lb/in with forces of 2 to 2.5 lb/g have proved to be extremely satisfactory for FBW aircraft. Designed to the phase rate and gain margin criteria discussed above, the attitude gain at the PIO frequency is only some 0.5 deg/in. Case 4D (28) had very poor phase rate and low PIO gain margin. With a gradient of 22 lb/in and 6.9 lb/g it had an attitude gain of 7 deg/in at the PIO frequency. Not surprisingly it suffered from continuous pitch oscillations and severe tracking PIO, an example shown being at ±2 degrees amplitude with very small stick motions, earning ratings of 8 and 9.

6 The Unstable Combat Aircraft

The differences in handling qualities between stable and superaugmented unstable aircraft range from the profound to the subtle, spreading from low frequency long term responses equivalent to the phugoid mode to high frequency short term responses equivalent to the short period mode. Unusual attitude induced pitch effects are also introduced. Despite this, a pitch rate demand FCS can provide an unstable aircraft with excellent handling which in some respects may be superior to the conventional. Well damped, precise and self-trimming attitude control add up to a low workload for the pilot in combat tasks. The different qualities required for the landing task can be provided equally easily.

Before handling qualities are considered at all, it is essential to ensure good gain and phase margins in the FCS and high robustness to withstand the effects of aerodynamic variations from the nominal, which can include store effects as well as uncertain derivative values, and of control system performance tolerances. Reduced pitch stability in particular has effects on the response behaviour which can be utterly different from the conventional and needs to be guarded against. Achievement of this aim can require considerable control filtering. All the hardware lags, software delays, anti-aliasing, notch and control filters must be included in the subsequent handling analysis and design. Flight simulation must model these accurately and present the responses in displays which do not add significantly to the lags or delays, the iteration rate preferably being at least 200 cps. With this standard, correlation of handling in simulation and flight has been excellent.

These methods were developed as a design tool. No attempt has been made to construct a set of boundaries for Level 1, 2 and 3. The designer of a FBW FCS can be content with a smaller range of near optimum behaviour. The handling qualities can be conventionally divided into the short period at constant speed and the long period affected by speed variations.

6.1 Short Period Characteristics

Figure 14 shows an example of the super-augmented pitch response of an unstable aircraft before and after the handling qualities optimisation process. The basic response contains three subsidences, one of them very long, and two oscillations, the short period and actuation modes. It is possible that for some configurations the filters will generate a second short period oscillation. The response is very well damped but sluggish, with low CAP, a long time to the pitch rate peak and considerable attitude overshoot. Flight path control appears reasonably good and steady states are reached within two seconds. Moderate high order characteristics are evident in the pitch rate and acceleration responses. The frequency response shows the overshoot by the lag at low frequency, with a less than optimum PIO gain margin and just satisfactory phase rate. Aircraft target tracking would certainly be poor but a fixed target would probably be acquired fairly easily. PIO is unlikely and would be mild if it occurred.

This handling is the consequence of the control filtering which cannot be altered without affecting the stabilisation. Command path filtering is used to obtain the desired handling, with no influence on the closed loop stability. It is often desirable to commence the optimisation process with the equivalent of a feedforward command from the stick to the control surface(s), scheduled with speed and probably angle of attack if the aerodynamics are significantly nonlinear, to provide a basic CAP value which can be chosen at will. Such a term is effective at high frequencies but is suppressed in the steady state by the integral trim. A value of 30 deg/sec^2/g is used here, experience showing that a higher value is not beneficial except at landing conditions and can cause airframe reactions detectable by the pilot. Similar effects can be obtained by stick filtering but the required scheduling is more complicated.

The optimisation is completed by the addition of the stick filters. Sometimes none are necessary, but usually there will be one, often two and rarely three lag-lead pairs to shape different frequency ranges in the response. In this example there are two pairs. The result is a CAP of 18 deg/sec^2/g, zero attitude dropback with moderate and fairly fast pitch rate overshoot, a flight path time delay of less than 0.5 seconds (ie 100 metres), and completely negligible high order effects. The frequency response is K/S-like at low frequency, the optimum for attitude tracking (12) and allowing a satisfactory pilot gain of 2 deg/lb despite the low stick force of 2.5 lb/g. The PIO gain margin and phase rate are excellent. All these indicate extremely good handling for all Cat.A tasks, free from PIO tendencies.

The optimised handling qualities for the landing approach can be predicted from this example. As the value of T_{θ_2} will be about 1.6 seconds a satisfactory flight path time delay of about 1 second requires the attitude dropback to be tuned to 0.6 seconds. In a comparable low order aircraft with a damping ratio of 1.0 this would be achieved by a short period frequency of 2 rad/sec, a pitch rate overshoot of 1.55 at 0.82 seconds, and a CAP of 55 deg/sec^2/g. Similar though not identical values would be expected in the super-augmented example, with all parameters inside their optimum ranges for this task. The frequency response aims are for the same PIO gain margin and phase rate and for the bandwidth frequency at 120 degrees phase lag to lie between 0.25 and 0.5 cps (5).

It is noteworthy that despite the significant increase in the overall order of the FCS due to the addition of the stick filters the high order handling effects have been nearly eliminated, in marked contrast to the disastrous effects of a single lag as discussed earlier. Selecting the filters is an interactive process at a graphics terminal, where the qualitative method is ideally suited to direct visual design. Once learned, handling assessment by these means can require no more than a pencil, a ruler and some mental arithmetic for an accurate result.

Gross manoeuvring in an unstable aircraft poses a special problem in the design of the hydraulic actuation system. The control surface travel is much greater than in a stable aircraft because it must first move in the conventional direction for the pitch acceleration and then reverse to the opposite quarter to decelerate and trim. The total travel can be considerable in a pull-up from level flight to maximum angle of attack which could be above 30 degrees. High surface rates can be required for a fast response, yet rate saturation can cause loss of control. The trade-off between response time and the mass and power offtake of the hydraulic system is particularly sensitive. Limitation of gross pitch response rate is implemented more effectively at the stick input rather than by actuator rate limits. The handling design methods given here ensure that there will be no large sustained PIO motion to drain the hydraulics.

Carefree handling which permits unrestricted stick inputs while respecting the airframe limits needs angle of attack and normal acceleration to be used in the demand path. Similar short period handling can be generated for these modes by the same methods. If they are designed to the same gain and phase margin characteristics all three modes are effectively interchangeable. It is possible to blend from one mode to another to make full use of the highly desirable pitch rate mode for straight flight in any direction and of the other modes for limiting g and angle of attack.

Response rate restrictions can flatten the pitch acceleration from its normal sharply peaked response, but this high order effect is of no significance.

6.2 Phugoid and Landing Characteristics

The phugoid mode is suppressed in a superaugmented pitch rate demand FCS. No trimming is required with speed variation or in climbing, diving and inverted flight, greatly reducing the pilot's workload in a combat aircraft. The aircraft goes where it is pointed. At and below the minimum drag speed, there is a high risk of an inadvertent drift into the stall at constant attitude, reducing speed and increasing sink rate. The landing flare is difficult because an unnaturally small stick input must be used instead of the usual rearwards movement which would cause ballooning. The tendency to hold a constant attitude is favourable after touchdown if bounces occur.

Normal acceleration demand also suppresses the phugoid. There is no level flight trimming, but it is necessary in climbing, diving and inverted flight which increases the pilot workload. The inadvertent stall at low speed tends to be more violent because the FCS pitches the aircraft up in its attempt to maintain the g beyond the lift break. The landing flare again requires negligible stick input but after touchdown any tendency to bounce is exacerbated because the FCS pitches the nose down in response to the bounces. With angle of attack demand the usual phugoid is present, and trimming is required in all variations of speed and flight path. Though once thought to be essential, such trimming becomes disliked by pilots who have experienced pitch rate demand control. On touchdown the reduction in a.o.a. at constant attitude may induce the FCS to pitch the nose up. In all systems it is necessary to inhibit the integrator when on the ground.

The addition of a selected amount of angle of attack into the pitch rate demand loop will produce a phugoid with any desired stick force variation with speed and a more conventional landing flare. This signal is not always available, eg after probe failure. It can be replaced in upright flight by a nose down pitch rate demand with reducing speed, requiring the pilot to pull the stick back or to trim it off, giving conventional control in the flare and also in the take off. It will protect the pilot from inadvertent stall in level flight, and the extent to which it will also do this in a decelerating climb can be designed in according to requirements. A vestigial phugoid will be introduced, as discussed in 6.4. With these improvements a pitch rate demand FCS can provide entirely satisfactory handling for all flight tasks at any speed with the exception of manoeuvre limiting.

In the landing rollout with the nosewheel off the ground, the stability reference point is moved from the CG to the wheels. The stability is reduced on any aircraft but it can produce more pronounced effects with a superaugmented FCS. Although this phase normally lasts only a few seconds, it is likely to represent the test pilot's first experience of the dynamic handling in the usual high speed taxi runs before the first flight. It should always be investigated.

6.3 Attitude Effects

The relationship between pitch rate and angle of attack varies with flight path angle. In a loop at constant pitch rate and speed, there is a 2g less acceleration over the top than at the bottom with a corresponding reduction in angle of attack. This is especially pronounced at low speed and with a pitch rate demand FCS can result in low g when inverted with a constant stick demand. If more g is pulled here then the angle of attack increase in the descent may rapidly become excessive unless backed off. For a constant pitch rate there is also 1g less acceleration in a steeply banked level turn.

With a g demand FCS a constant stick input leads to increased angle of attack at the reduced speed over the top. With an angle of attack demand the behaviour is conventional. For a superaugmented aircraft the best combination is the blending of pitch rate and angle of attack systems described above. In a reversionary FCS with only pitch rate available, effective manoeuvre limiting can be achieved by the use of attitude information, if this is reliably available. It is arguable that this is a luxury for a fairly remote failure case, and it is possible to achieve excellent combat capability without it. Accurate loops can be easily achieved with pitch rate alone, and the main problem to be addressed is the choice of a compromise demand gain which allows enough pitch rate in a low speed loop without producing an excessive amount in level flight.

When the lift vector is directed to one side of the vertical by banking, even if the lift is not increased to maintain level flight, a pitch rate will develop. A pitch rate FCS will try to suppress this by reducing the angle of attack, and so there will be a more pronounced tendency for the flight path angle to change downwards. This is most marked at low speed where the vertical g deficiency produces a more rapid rate of change. The pitch rate equivalent to the required extra g in a coordinated level turn will produce a greater g when the wings are levelled, with a sharper pitch up. The effects are noticeable in simulation and can give a first impression of undemanded pitching, but it is easily adapted to and does not present a flight problem.

In rolling manoeuvres the same resistance to pitching causes the angle of attack to vary. This gives excellent handling in slow rolls but it upsets the coordination in rapid rolls. Although the handling is different from the conventional it is not necessarily less acceptable. It is also possible to minimise the effect in the control law design.

6.4 Turbulence Effects

Superaugmented aircraft can be expected to have a very low pitch response to turbulence due to the high attitude stiffness. If the airframe is unstable it will naturally pitch upwards instead of downwards in response to an upgust before the FCS reacts, but the difference in g levels is usually very small. Pilots greatly prefer a stable attitude behaviour at the expense of increased heave or bumpiness in turbulence because this gives confidence that full control is being maintained.

If the heave is unacceptable either for ride comfort or for weapon performance, it is better to reduce it by direct lift gust alleviation if possible. Generally the addition of normal g to a pitch rate demand FCS or g demand itself will not improve the accuracy of the flight path and will probably amplify the disturbances in attitude.

Pitch response to airspeed variations caused by the phugoid mode in gusts or wind shear is especially significant in the approach. The effects were studied in the Cornell T-33 (32). Augmentation by increasing the pitching moment due to airspeed caused excessive attitude response up to the short period frequency. This is shown in Figure 15 with the gust responses of conventional and superaugmented combat aircraft. On the latter a pitch rate demand to provide apparent static stability creates only a small phugoid effect with an unchanged response at higher frequencies. Satisfactory static stability can therefore be added to a superaugmented aircraft with little of the other effects of a phugoid. Such aircraft are found to be excellent for instrument flight approaches.

6.5 The Minimum FCS

The flight envelope will be severely restricted after failures leaving only the pitch rate gyros working in a fixed gain mode. The flight limits can be determined by flight simulation if it is of the standard specified above. The speed at which the damping of the actuation mode around 15 to 20 rad/sec becomes neutrally damped will be correctly computed and visibly presented, so that the pilot can set a maximum speed below this which he considers to have tolerable handling. Only gentle manoeuvres can be permitted in this state. If large gusts can cause system instability and loss of control the permitted speed could be even lower.

The lower end of the speed range will be set by degraded handling, typically increasingly low damping coupled with a frequency which can decrease to about 1 rad/sec. This is similar to the low order condition with unpredictable pitch response because of the long period overshoots, resulting in the pilot overdriving in a slow PIO. The design discussed above will largely retain a good CAP which gives an immediate response to stick inputs, but this only partly alleviates the problem as was found in the 1-A case discussed in 5.1.1. This effect tends to maintain satisfactory high order PIO resistance at the higher frequencies.

The effective speed range can be extended by switching gains with undercarriage selection. The landing case can be centred at or near the normal approach speed to give very good handling, only the artificial static stability being absent. The wheels up speed range must overlap sufficiently to respect the wheels down selection limit and the upper limit may be well below normal operational speeds. The implications following the last failure before the fixed gain mode occurs will affect the continuation of the mission, but there are ways in which the gap can be bridged.

7 Conclusions

It has been shown that aircraft pitch short period handling qualities can be described in detail by the individual equivalent response parameters discussed in this paper. They can be identified in past low order aircraft handling qualities flight experiments and they indicate strong conformity in results previously considered contradictory and inconsistent. They also describe the basic handling of aircraft with high order characteristics introduced by fly by wire flight control systems, but additional parameters are identified which are mainly related to pilot induced oscillations.

Unstable combat aircraft, stabilised primarily by integral pitch rate manoeuvre demand or superaugmentation, have responses which are a combination of airframe and control system dynamics and cannot be described by conventional criteria. Excellent short period handling qualities can be assured in their design by the equivalent response assessment methods and the elimination of pilot induced oscillations. The methods are exceptionally easy to use and retain total visibility of all aspects of handling. Optimisation by command path filtering is powerful and effective, to a large extent independent of the task of feedback stabilisation.

The characteristics exhibited in the long period mode, landing control and attitude effects in manoeuvres are unconventional but are either satisfactory or can be made so by additional command modes. The highly damped, self trimming and precise attitude and flight path control combine to give an overall quality of handling unmatched by conventional aircraft.

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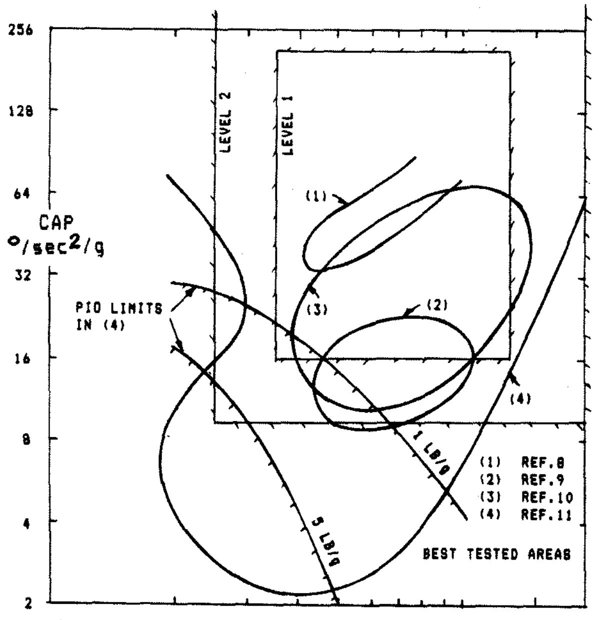


FIGURE 1 CURRENT SHORT PERIOD THUMBPRINT

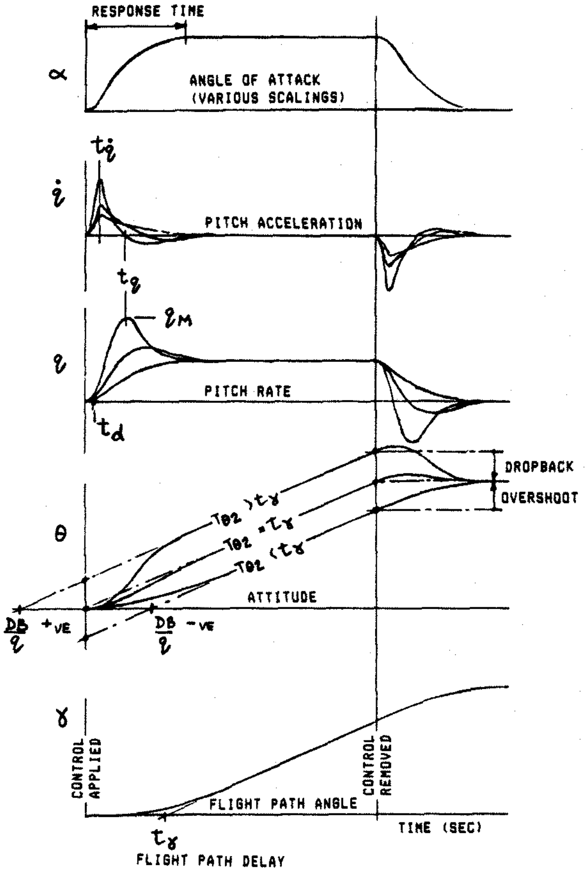
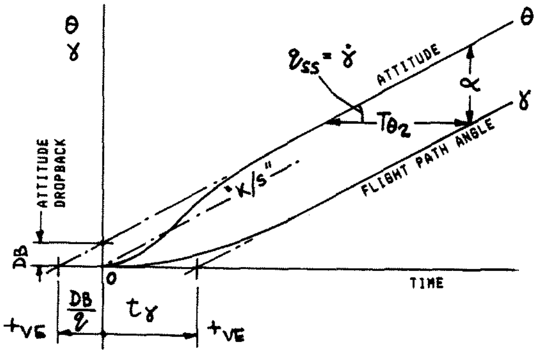


FIGURE 2 PITCH SHORT PERIOD TIME RESPONSES



$$q_{ss} = \dot{\gamma} = \frac{g}{V}(n - \cos\gamma)$$

$$\left.\begin{aligned} q_{ss} &= \frac{g}{V}\Delta n \\ \gamma &= \int \frac{g}{V}\Delta n \end{aligned}\right\} \text{LEVEL FLIGHT APPROXIMATION}$$

$$n/\alpha = \frac{V}{g} \times \frac{1}{T_{\theta 2}}$$

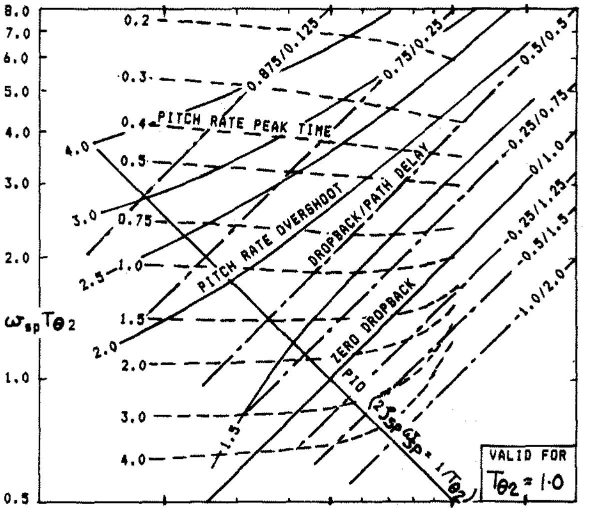
$$\frac{\alpha}{q} = T_{\theta 2}$$

$$T_{\theta 2} \doteq \frac{1}{L_\alpha}$$

$$t_\gamma = \frac{2\zeta_{SP}}{\omega_{SP}}$$

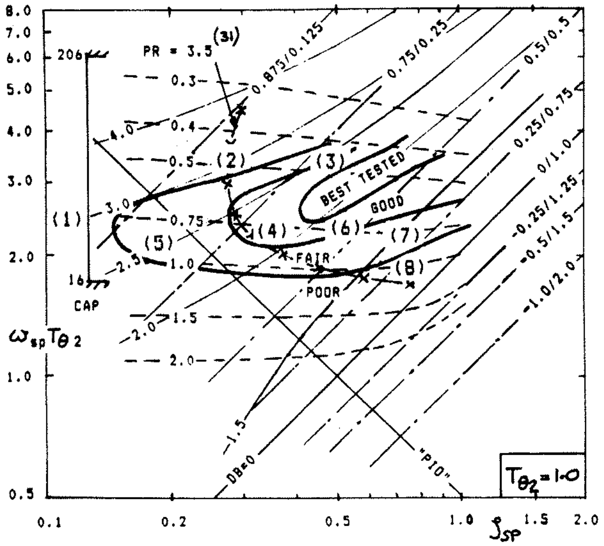
$$\frac{DB}{q} = \left(T_{\theta 2} - \frac{2\zeta_{SP}}{\omega_{SP}}\right)$$

FIGURE 3 FLIGHT PATH - ATTITUDE RELATIONSHIPS



- MULTIPLY DASHED LINE VALUES BY $T_{\theta 2}$
- SOLID LINE VALUES CONSTANT

FIGURE 4 NEW SHORT PERIOD THUMBPRINT



(1) DANGEROUS OSCILLATION
(2) FEAR OF GUSTS, RESPONSE TOO FAST, FORCES TOO LIGHT
(3) PILOT INDUCED OSCILLATIONS
(4) OSCILLATIONS
(5) SLUGGISH, OSCILLATORY
(6) SLUGGISH
(7) MORE SLUGGISH, HEAVY STICK FORCES
(8) VERY SLUGGISH, VERY HEAVY STICK FORCES

FIGURE 5 B-26 THUMBPRINT (Refs.8, 31)

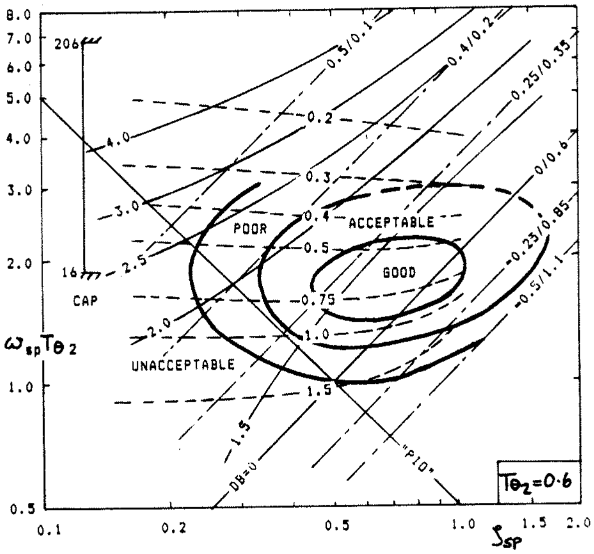
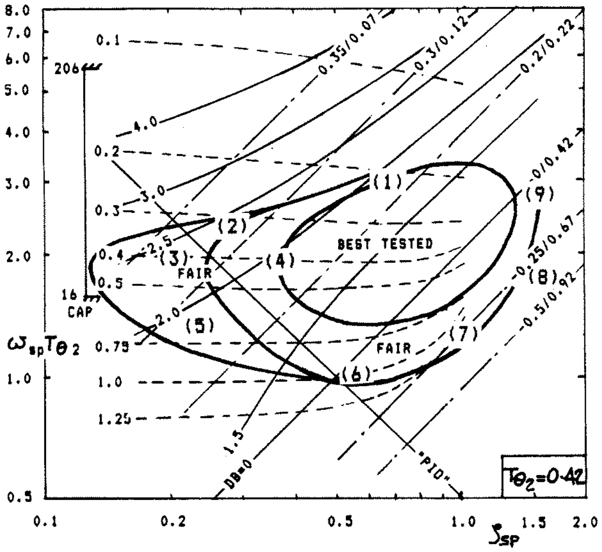


FIGURE 6 F-94 THUMBPRINT (Ref.9)



(1) VERY HIGHLY RESPONSIVE, ABRUPT, TOO RAPID
(2) VERY SENSITIVE, OSCILLATORY, TOO CLOSELY COUPLED
(3) DANGEROUS, HIGHLY OSCILLATORY, VERY DIFFICULT TO TRACK AND TRIM
(4) A LITTLE SENSITIVE, OSCILLATORY, A LITTLE DIFFICULT TO TRACK AND TRIM
(5) OSCILLATORY, OVERSHOOTS, DIFFICULT TO TRACK
(6) NOT FIGHTER TYPE, SLUGGISH, TENDS TO DIG IN
(7) BOMBER TYPE, NOT MANOEUVRABLE, VERY SLOW, PILOT MUST LEAD THE AIRCRAFT
(8) STIFF AND SLUGGISH, GOOD FLYING BUT NOT A FIGHTER
(9) SLOW, HESITATES, NOT MANOEVRABLE

FIGURE 7 F-94 THUMBPRINT (Ref.10)

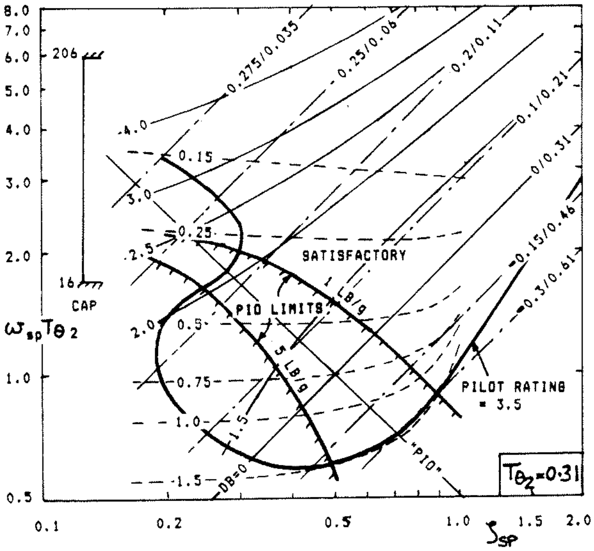
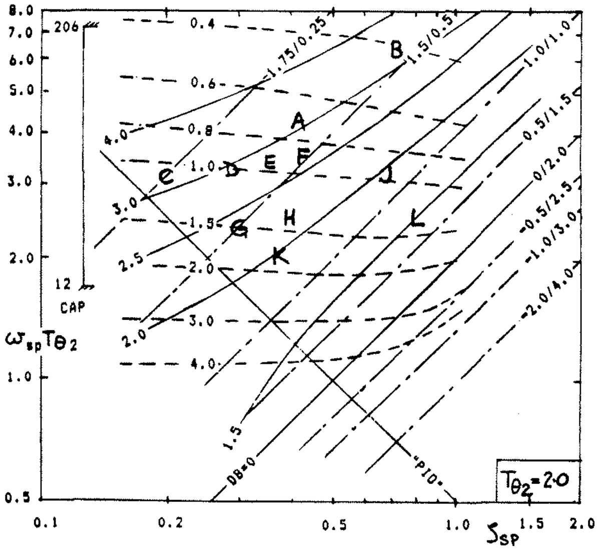


FIGURE 8 LAHS THUMBPRINT (Ref.11)



CASE	RATING	COMMENT
A	2.7 2.9 3.9	LONG TIME TO DAMP
B	2.0 3.2 4.0	SLIGHT OVERSHOOT AND DROPBACK
C	6.3 5.3	LOW DAMPING, PIO
D	4.2 3.8 4.1 4.0	
E	2.1 2.2 4.0	BOBBLES
F	2.5 3.6 1.8	VERY GOOD
G	5.4 4.6 5.5 4.5	
H	4.2 4.0 3.5	
J	2.0 2.0 3.0 3.2	LITTLE SLUGGISH
K	7.3	SLUGGISH, OVERSHOOTS
L	2.6 2.8 3.7 3.5	SLUGGISH

FIGURE 9 NF-8D THUMBPRINT (Ref.23)

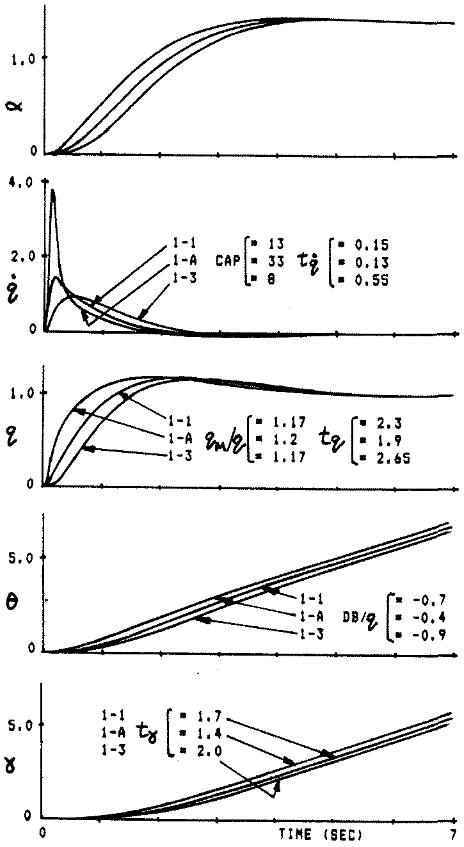


FIGURE 11 CALSPAN LAHOS EXPERIMENT EXAMPLES

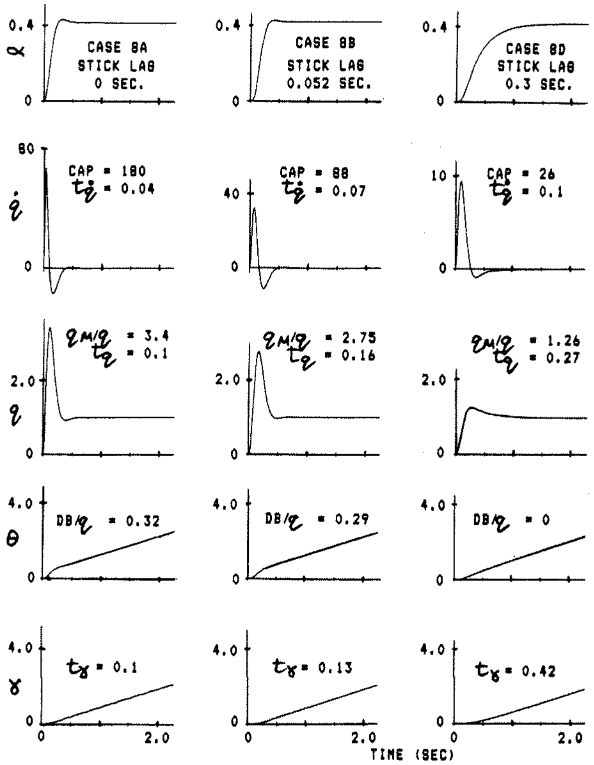


FIGURE 10 CALSPAN FIGHTER EXPERIMENT EXAMPLES

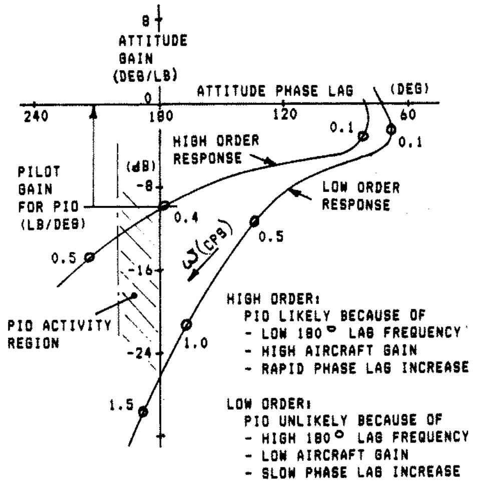


FIGURE 12 HIGH AND LOW ORDER FREQUENCY RESPONSE

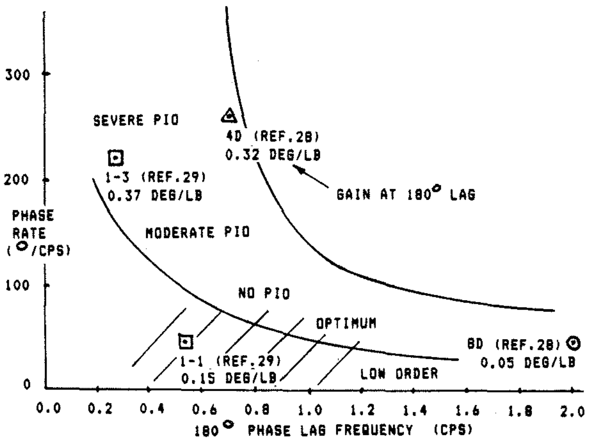


FIGURE 13 TRENDS OF HIGH ORDER PHASE RATE

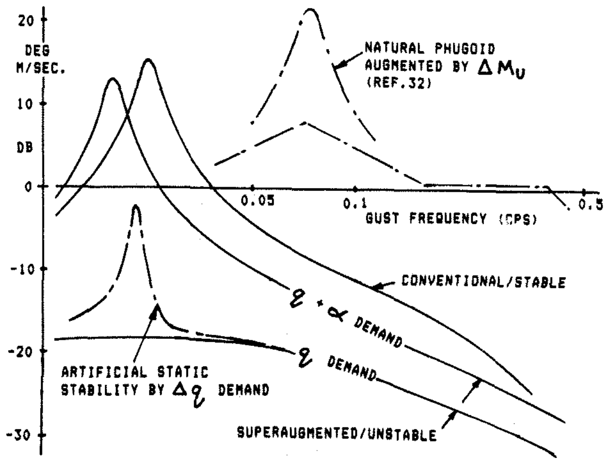
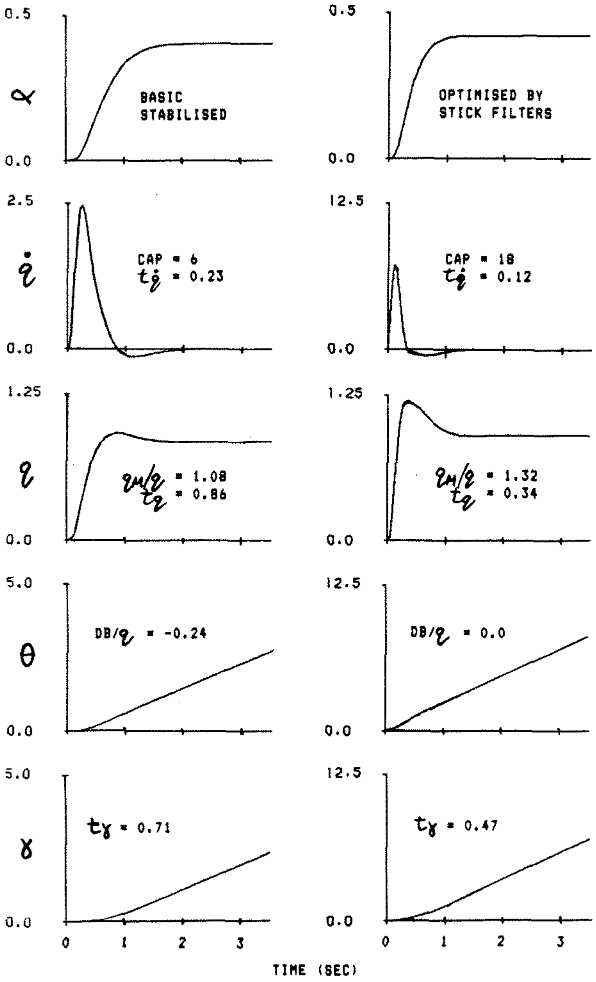
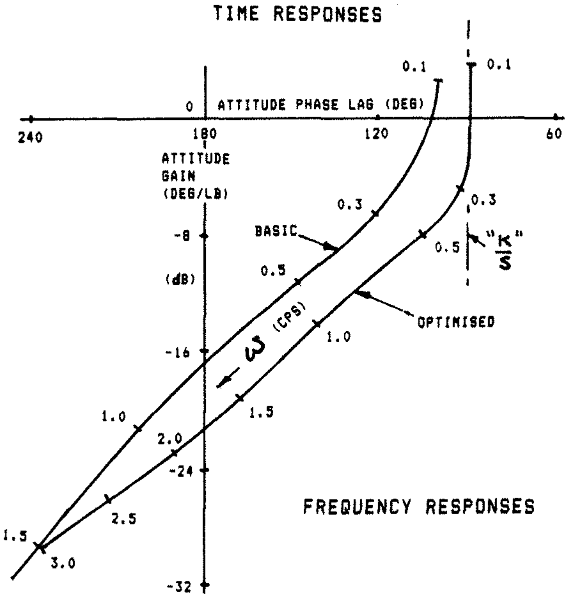


FIGURE 15 PITCH RESPONSE TO HORIZONTAL GUSTS



TIME RESPONSES



FREQUENCY RESPONSES

FIGURE 14 OPTIMISED SUPERAUGMENTED RESPONSES