An Approach to the Determination of Aircraft Handling Qualities Using Pilot Transfer Functions

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It is shown that a correlation exists between pilot-aircraft system closed-loop characteristics, determined by using analytical expressions for pilot response along with the analytical expression for the aircraft response, and pilot ratings obtained in many previous flight and simulation studies. Two different levels of preferred pilot response are used. These levels are 1) a static gain and a second-order lag function with a lag time constant of 0.2 sec and 2) a static gain, a lead time constant of 1 sec, and a 0.2-sec lag time constant. If a system response with a pitch-angle time constant of 2.6 sec and a stable oscillatory mode of motion with a period of 2.5 sec can be achieved with the first level pilot model, it is shown that the pilot rating will be satisfactory for that vehicle. Further, if an altitude response with a stable oscillatory mode of motion with a period of 5 sec can be achieved, the vehicle will be rated satisfactory. If the second level pilot model is required to achieve these system response characteristics, the aircraft will be rated acceptable-unsatisfactory.

Nomenclature

h	= altitude, ft (m)
K_1	= pilot model static gain
L_α	= normalized lift-force derivative, per sec
L_{δ_e}	= normalized control-lift derivative, per sec
M_q	= normalized damping-moment derivative in pitch, per sec
M_α	= normalized pitching-moment derivative, per sec^2
M_{δ_e}	= normalized pitching control-moment derivative, per sec^2
P_h	= closed-loop period of the altitude mode of motion, sec
P_α	= closed-loop period of the angle-of-attack mode of motion, sec
s	= Laplace operator, per sec
T	= closed-loop time constant, sec
T_1	= pilot model lead time constant, sec
T_2	= pilot model lag time constant, sec
T_{θ_2}	= open-loop aircraft lead time constant, sec
V	= velocity, ft/sec (m/sec)
x	= displacement, ft (m)
α	= angle of attack, rad
γ	= flight-path angle, rad
δ	= control deflection, rad
ϵ	= displayed error, rad
ζ	= damping ratio
ζ_h	= damping ratio of the altitude mode of motion
ζ_α	= damping ratio of the angle-of-attack mode of motion
θ	= pitch angle, rad
ω_n	= open-loop aircraft undamped natural frequency, rad/sec
ω_f	= control actuator undamped natural frequency, rad/sec

Subscripts

c	= command
h	= altitude
ϵ	= error
θ	= pitch

Introduction

IT has been shown in Refs. 2 and 3 that models of human response can be used to predict system performance of manually controlled vehicles. It would be beneficial if these pilot models could also be used to predict pilot acceptance of future vehicles.† Since a large amount of previously obtained data is available on pilot ratings of aircraft as a function of aircraft characteristics, criteria for predicting pilot ratings are established in this paper by showing the correlation between calculated pilot-vehicle system characteristics, determined by using pilot models, and the previously obtained pilot ratings of aircraft. The criterion that is developed involves specified levels of preferred pilot response characteristics and specified pilot-vehicle closed-loop system characteristics. These criteria are suggested for use in predicting pilot ratings of future vehicles.

Pilot Models

The pilot models which will be used in this paper are described in the following manner. For single-loop control tasks, the model form used consists of the following elements: a static gain and a lead time constant which constituted a commanded control deflection; and a second-order, critically damped lag function, which represents the dynamic response of the arm in executing the command for the control deflection. In transfer function form, the model is

$$\delta/\epsilon = K_1(1 + T_1s)/(1 + T_2s)^2 \qquad (1)$$

Typical values for the coefficients for various plant dynamics are given in Table 1. These values are taken from Refs. 4 and 5.

It can be seen from this table that when a pilot is controlling a very easy-to-handle plant, such as a pure rate vehicle, $2/s$, that the lag time constant of the pilot's response T_2 is as large as 0.3 sec, with 0.2 sec being a very common average value. Also, the lead time constant, T_1, is very often zero. However, sometimes a value of up to 0.67 sec is measured. As the control difficulty of the plant is increased by increasing the lag of the plant, additional lead is added to the pilot's response, and the pilot's lag is reduced. In the extreme case of a plant $10/s^2(s + 1)$, the lead time constant is increased to the maximum measured value of 1.0 sec, and the lag time constant is reduced to 0.05 sec.

In one experiment reported in Ref. 4, pilot response was measured while controlling a plant with an aircraft pitch response type of characteristic. The plant transfer function was

$$\theta/\delta = 10/s(s^2 + 3s + 10) \qquad (2)$$

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† This thought has been discussed previously in Ref. 1.

and the measured pilot transfer function was

$$\delta/\theta_e = 0.86(1 + 0.7s)/(1 + 0.14s)^2 \tag{3}$$

It can be seen from this transfer function that the lag and lead time constants are within the ranges noted in the previous paragraph. It is assured that the values given for maximum and minimum time constants given before will also apply to aircraft-type plant dynamics.

The static gain K is always adjusted to provide a desired system response characteristic. That these system characteristics can be identified and defined is shown by the results obtained in Ref. 3. In Ref. 3, a wide variety of plants, control gains, display gains, and subjects were tested. In spite of this great variety of system elements, the predominant system closed-loop characteristic always fell within a very restricted range. For the type of plants being considered here, that is, plants of the form K/s and K/s^2, which have no static stability of their own, the predominant system characteristic was an oscillatory mode of motion. The frequency of this oscillation always fell within the range of 4–2 rad/sec, and the oscillation was always stable. From these results, it is concluded that the pilot uses the predominant system characteristic as the criterion to set his static gain.

The predominant system characteristic is not always an oscillatory mode of motion. With the aircraft pitch response type of plant, the predominant system characteristic was a first-order factor. In the case mentioned before, the time constant of this first-order response was 1.7 sec. There is also an oscillatory mode of motion included on the system response in this case, and it is also shown that this oscillatory mode of response is stable.

From these examples, it is concluded that the system response with which the pilot will concern himself can be of two different types. The first is the case when the predominant system characteristic is an oscillatory mode of motion; the pilot will be concerned with the frequency and damping of this mode of motion. In the second case, when the predominant system characteristic is a first-order mode of motion, the pilot will be concerned with the time constant of this mode and the stability of the other oscillatory modes of the response. In either case, the system time characteristic that the pilot will strive to achieve is around 2 sec.

If the control task is a multiloop problem, where there is a second variable (such as altitude or horizontal displacement) which is controlled by the manipulation of an inner-loop variable (such as pitch angle), it is necessary to specify an outer-loop pilot model in a series with the inner-loop pilot. In Ref. 6 it is shown that in the multiloop control task of lunar module hover, where the outer-loop variable is horizontal translation and the inner-loop variable is pitch angle, that the series arrangement of the pilot model does give a true representation of human pilot response. In this task the outer-loop dynamics were

$$x/\theta = 5.36/s^2 \tag{4}$$

and the outer-loop pilot model was

$$\theta_c/x_e = 0.009(1 + 9.2s)/(1 + 0.1s)^2 \tag{5}$$

It was also shown in Ref. 3 that the lag function included in the outer-loop pilot model is not really required to properly represent the pilot. The outer-loop variable, translation, is controlled at such a low frequency that a lag of the magnitude of 0.1 sec does not influence the closed-loop response. Reference 7 has shown similar results for the case of hover with a helicopter. Again, a series arrangement was used to represent the pilot, and the outer-loop model was

$$\theta_c/x_e = 0.027(1 + 0.4s)e^{-0.08s} \tag{6}$$

where a small time delay is used instead of a lag function.

Table 1 Measured pilot response

Dynamics	Pilot transfer function		
$\frac{2}{s}$	$\frac{3.26}{(1 + 0.25s)^2}$	$\frac{3.2(1 + 0.33s)}{(1 + 0.33s)^2}$	$\frac{0.7(1 + 0.67s)}{(1 + 0.33s)^2}$
$\frac{10}{s(s + 1)}$	$\frac{0.5(1 + 0.3s)}{(1 + 0.1s)^2}$	$\frac{0.36(1 + 0.91s)}{(1 + 0.18s)^2}$	
$\frac{10}{s^2(s + 1)}$	$\frac{0.29(1 + 1.0s)}{(1 + 0.05s)^2}$		

Reference 8 also used the series arrangement to represent the pilot in the case of altitude control for an airplane. In this case the outer-loop pilot was

$$Y_h = \theta_c/h_e = 0.4/(1 + 0.1s) \tag{7}$$

In this case, no lead was required and again a very short time constant lag function was included.

In all three of these Refs. 5–7, the outer-loop variable is controlled at a lower frequency than is the inner-loop variable. Also, when the outer loop is closed around the inner loop, the resulting modes of motion couple with each other, and further restrictions on the outer-loop static gain can result from requirements to maintain stability of the short-period inner-loop variable.

Based on the results of these single-loop and multiloop experiments, different levels of preferred pilot response are proposed. For single-loop or inner-loop control, the levels are the following:

1) The pilot would prefer to operate as a simple amplifier with a lag time constant of 0.2 sec. It is hypothesized that if suitable system response characteristics can be achieved with this type of pilot response, the system will be judged to be satisfactory.

2) If some compensation is required on the part of the pilot in order to stabilize the system, the compensation will take the form of lead, with a maximum time constant of 1 sec. It is hypothesized that if suitable system characteristics can be achieved with this pilot response, the system will be judged acceptable but unsatisfactory.

3) If further compensation is required, it will be supplied by reducing the lag time constant to 0.05 sec. It is hypothesized that if this compensation is required to stabilize the system, the system will be judged to be unacceptable.

For the outer-loop response of the pilot, similar levels of preferred response are proposed. They are the following:

1) The pilot would prefer to operate as a simple amplifier. It does not appear to be necessary to specify any particular value for lag in this case, because the expected values of this lag will not influence system response.

2) If additional compensation is required, it will take the form of lead. It appears that outer-loop lead time constants can be quite large.

The closed-loop system characteristics which must be satisfied with these different levels of preferred pilot response are as follows. For inner-loop or single-loop variables, the system response must be stable with a time characteristic as low as 2 sec. For outer-loop variables, the response must be stable, and, as experiments on pilot response have shown, the time characteristic can be somewhat longer than for single-loop variables. In the present investigation, a search will be made to determine a time characteristic for altitude which will correlate with the pilot rating boundaries. If a single value can be found that will agree with the various boundaries determined in flight tests, it will be considered a very significant result.

The suggestion that a pilot would prefer to operate as a simple amplifier was made several years ago in Ref. 9. The present investigation attempts to expand the idea to show a correlation with the whole range of pilot opinion.

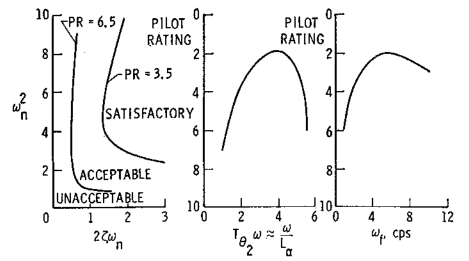


Fig. 1 Pilot ratings with short period ω_n − $2\zeta\omega_n$, L_α, and actuator frequency ω_f.

Pilot Rating Data

A large amount of data on pilot ratings as a function of various aircraft parameters has been accumulated in the past. Perhaps the most fundamental relation is that established between pilot ratings and aircraft longitudinal short-period characteristics, ω_n and $2\zeta\omega_n$. The boundaries dividing pilot ratings of satisfactory from acceptable-unsatisfactory and acceptable from unacceptable as a function of ω_n^2 and $2\zeta\omega_n$ are shown on Fig. 1 for a landing condition. These boundaries were taken from Ref. 10 for a landing condition with good (front side) drag characteristic.

Pilot ratings have also been shown to be a function of T_{θ_2} where

$$1/T_{\theta_2} = (M_{\delta_e}L_\alpha - L_{\delta_e}M_\alpha)/M_{\delta_e} \approx L_\alpha \tag{8}$$

The relationship has been defined in many ways. In Ref. 11, it is defined by the statement that pilot opinion will be the best when

$$T_{\theta_2}\omega_n = 4 \tag{9}$$

Also, pilot ratings have been shown to be a function of control actuator dynamics. In Ref. 12, it is shown that if the elevator actuator is represented by a second-order transfer function, and the frequency of actuator characteristic response is less than 20 rad/sec, pilot ratings will be seriously degraded.

It is proposed, therefore, to show that pilot-airplane system characteristics obtained using the various levels of preferred pilot response defined in the previous section will correlate with the pilot ratings as a function of ω_n − $2\zeta\omega_n$, T_{θ_2}, and actuator dynamics response.

Aircraft and System Representation

The airplane is represented by the two-degree-of-freedom longitudinal equations of motion

$$\dot{\alpha} - \dot{\theta} = -L_\alpha \alpha \tag{10}$$

$$\ddot{\theta} = M_q\dot{\theta} + M_\alpha \alpha + M_{\delta_e}\delta_e \tag{11}$$

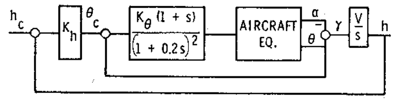
and the relationship for altitude

$$\dot{h} = V(\theta - \alpha)$$

Two different values of L_α were investigated, $L_\alpha = 0.585$ and $L_\alpha = 1.3$. M_{δ_e} was arbitrarily assumed to be equal to 1.0. The values of M_q and M_α were adjusted to provide a wide range of airplane short-period characteristics ω_n^2 and $2\zeta\omega_n$. It is not necessary to state a given value for velocity V. In this analysis, it is assumed that the pilot will always adjust his static gain so as to achieve a certain period for the system response. It can be seen that the over-all outer-loop static gain for the pilot-airplane combination will be K_hV; and therefore it is always the product which will be given, and it will be assumed to be independent of the value of V.

For altitude control, the complete block diagram of the pilot-airplane combination is shown in Fig. 2. As can be seen, the outer-loop pilot model is assumed to be just a static gain. For attitude control, the outer loop was discarded and just the inner loop was considered. The inner-loop pilot model

Fig. 2 System block diagram.



lag time constant was always assumed to be 0.2 sec and the lead time constant was either 0 or 1 sec.

Both attitude and altitude control will be studied because each of these modes of control is present in the different flight tasks that must be performed. Attitude control corresponds to long-range tracking; altitude control corresponds to landing approach, terrain following, and formation flying.

Results

First, the altitude response of the pilot vehicle system was determined for a wide variety of airplane characteristics with no lead included in the inner-loop pilot model. The inner- and outer-loop pilot model static gains were adjusted to give the best possible stable system response. It was found that two different definitions for best response were required. For the altitude control system, which was a sixth-order system, the response consisted of three oscillatory modes of motion. One of these modes was a very high frequency well-damped mode which corresponded to the control response of the pilot, and it could not be considered as having a critical influence on the total system response. The other two oscillatory modes of motion corresponded to the angle-of-attack response and to the altitude response of the system. For airplanes with high values of ω_n^2, the angle-of-attack mode frequency was quite high, and therefore was not a critical factor. The critical factors were the altitude mode of motion frequency and damping, and the damping of the angle-of-attack mode of motion. Therefore, the outer-loop and inner-loop pilot model's static gains were adjusted to as high a value as possible and still have a stable response, and the frequency of the altitude mode of motion was noted. For a value of L_α = 0.585, typical values for the period of the altitude mode of motion are noted in Fig. 3. The period is given because it is felt that the period can be more easily visualized, and thus will be more meaningful than will the frequency. The period of the angle-of-attack mode of motion is also given. It can be seen that for high values of ω_n^2, the altitude mode of motion period varied from 10 sec when $2\zeta\omega_n$ was low to 4 sec when $2\zeta\omega_n$ was high. From these results, it was decided that a period of 5 sec would define a useful boundary to be used to divide the plot into satisfactory and acceptable areas. Accordingly, the synthesis method described in Ref. 13 was used to define this curve. It was specified that the altitude mode of motion period should be 5 sec, and that the damping of the altitude mode of motion and the angle-of-attack mode of motion should be zero. The airplane, open loop, ω_n^2 and $2\zeta\omega_n$ values that would satisfy these conditions were then determined, and they are plotted on Fig. 3. It can be seen that this curve agrees well with one branch of the pilot rating curve for a landing task.

For low values of ω_n^2, a second definition for a suitable response was required. For low values of ω_n^2, the angle-of-

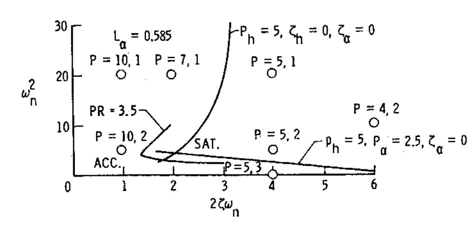


Fig. 3 Comparison of computed system characteristics using first-level pilot models (no lead) for altitude control and pilot ratings.

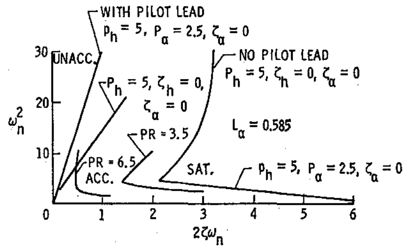


Fig. 4 Comparison of computer system characteristics using first- and second-level pilot models for altitude control and pilot ratings.

attack period became relatively long, and became the predominant and critical factor. Therefore, the pilot model static gains were adjusted to provide the shortest possible altitude and angle-of-attack periods while maintaining a stable angle-of-attack response. The damping of the altitude mode of motion was always positive under these conditions, and therefore was not a critical factor. Typical values for the altitude and angle-of-attack periods are again shown in Fig. 3. From these results and other considerations, it was decided that an angle-of-attack period of 2.5 sec would provide a useful boundary to be used to separate the satisfactory from the acceptable region of the plot. The synthesis method was again used; where, this time, the altitude period was specified to be 5 sec, the angle-of-attack period was specified to be 2.5 sec, and the angle-of-attack damping was specified to be zero. The values of ω_n^2 and $2\zeta\omega_n$ that would satisfy those conditions are shown in Fig. 3, and it can be seen that this curve agrees with the second branch of the pilot rating curve for the landing task.

Next, a 1-sec lead time constant was added to the inner-loop pilot model, and system response was again calculated. The same system characteristic as used before was again specified. The values of ω_n^2 and $2\zeta\omega_n$ which satisfy these criteria are shown on Fig. 4, and it can be seen that these values agree fairly well with the pilot rating boundary between acceptable and unacceptable aircraft for a landing task. With the linear, constant coefficient pilot response used on these computations, there is no restriction in the lower and negative regions of ω_n^2.

Next, attitude control, with no pilot model lead, was examined. For this system, a fifth-order system, the system response consisted of two oscillatory modes of motion and a first-order mode of motion. Again, one of the oscillatory modes was the control mode of motion, and was of no concern. For high values of ω_n^2, the frequency of the other oscillatory mode of motion was always high and therefore of no concern. The critical factors were the time constant of the first-order mode and the stability of the angle-of-attack mode. Therefore, the static gain of the pilot model was adjusted until the time constant was as low as possible with a stable angle-of-attack response. Typical values for these time constants are shown on Fig. 5, and it can be seen that they vary from 6 to 2 sec. From these results, it appeared that a value for the time constant of 2.6 sec would provide a useful bound-

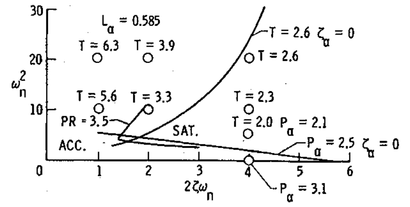


Fig. 5 Comparison of computed system characteristics using first-level pilot models (no lead) for attitude control and pilot ratings.

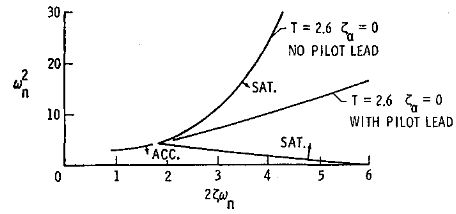


Fig. 6 Computed system characteristics using first- and second-level pilot models for attitude control.

ary. Again, the synthesis method was used to determine the values of aircraft ω_n^2 and $2\zeta\omega_n$ with which $T = 2.6$ and zero damping for the angle-of-attack mode of motion could be achieved. The resulting curve is shown on Fig. 5 and can be seen to agree well with the pilot rating boundary between satisfactory and acceptable.

For lower values of ω_n^2, the period of the angle-of-attack mode of motion becomes a critical factor. The curve which satisfies the specification for an angle-of-attack period of 2.5 sec and zero damping is shown on Fig. 5, and can be seen to agree well with the other branch of the pilot rating curve. The time constant is always less than 2.6 sec when these conditions are met.

From these results for altitude and attitude control, it is concluded that an aircraft which is rated satisfactory would be rated so on the basis of either altitude or attitude control tasks.

When lead is added to the pilot model for the attitude control task, the surprising result was that performance was degraded in the high ω_n^2 region, Fig. 6. As was true in the case with altitude control, the addition of lead eliminated all restriction in the low and negative ω_n^2 region. However, instead of moving the boundary for satisfactory control in the high ω_n^2 region to the left, as was the result with altitude control, the boundary was moved to the right. This would seem to be a very confusing situation in which the addition of lead would help the pilot bring the aircraft under better control for altitude control, but degrades the system for attitude control. However, pilot comments indicate that an exceptional amount of confusion does exist for aircraft which fall in this region. In Ref. 14, p. 128, pilot comments for an aircraft with the parameters $L_\alpha = 0.5$, $\omega_n = 0.7$ cps, $\zeta = 0.3$, which is indicated by the symbol on Fig. 7, indicate that altitude control is fair, whereas attitude control is poor because of a tendency for the aircraft to bobble. It is felt that these comments are in good agreement with the computed results.

Another condition which can be used to test the validity of the pilot models is to see if they can confirm the change in pilot ratings that occur when L_α is changed. The effect of L_α on pilot ratings has been summarized by the statement that pilots prefer that

$$T_{\theta_2}\omega_n \approx \omega_n/L_\alpha = 4$$

This formula indicates that for $L_\alpha = 0.585$, the preferred value for ω_n^2 is 5.5, which can be seen to correspond to the lowest value of satisfactory $2\zeta\omega_n$ for altitude and attitude control presented in Figs. 3 and 5.

The boundaries for the same system characteristics, with no lead in the pilot model, were also calculated with L_α increased to 1.3. These results are shown, together with the re-

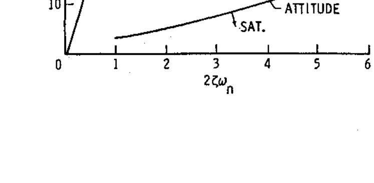


Fig. 7 Comparison of altitude and attitude control with second-level pilot models.

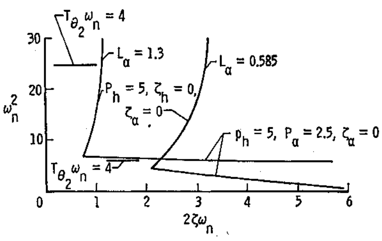


Fig. 8 Comparison of altitude control with first-level pilot model for two values of L_α.

sults for $L_\alpha = 0.585$ in Figs. 8 and 9. With $L_\alpha = 1.3$, the handling-qualities data indicate that the preferred value for ω_n^2 increases to 27. The computed system characteristics indicate that the satisfactory area of the $\omega_n^2 - 2\zeta\omega$ plot has been greatly expanded in the high ω_n^2 region with the location of $T_{\theta_2}\omega$ being within this expanded area. The satisfactory region is slightly restricted in the low ω_n^2 region for the higher value of L_α. Thus, it can be seen that the computations agree with the pilot ratings.

Pilot rating boundaries as a function of ω_n^2 vs $2\zeta\omega_n$ and T_{θ_2} and ω_n have been established by flight tests. It has been shown in the preceding paragraphs that pilot models can be used to reproduce these boundaries. One of the immediate advantages of the use of pilot models is that the combined effects of ω_n, $2\zeta\omega_n$, and T_{θ_2} can be computed, and these results are shown in Figs. 8 and 9. The combined effects of the three parameters have not been extensively checked in flight tests, but some recent results presented in Ref. 15 show good agreement with Fig. 8 in that the flight tests show that a low value of $2\zeta\omega_n$ is acceptable in combination with high values of ω_n^2 and L_α (or $1/T_{\theta_2}$).

A third influencing factor on pilot ratings that can be checked with the use of pilot models is the degrading effect of inserting control actuator dynamics in the control system. It has been shown that if the actuator dynamics have a natural frequency less than 20 rad/sec the pilot ratings will be drastically affected. Therefore, system characteristics were computed with actuator dynamics with a natural frequency of 10 rad/sec. This actuator would be expected to degrade the pilot ratings from two to four numbers on the Cooper scale. The control situation examined was attitude control with no lead and with $L_\alpha = 0.585$. The results are plotted in Fig. 10. As can be seen, the boundary for suitable system response is shifted to be more restrictive or, conversely, the response with a given aircraft is degraded by the addition of the actuator dynamics. For the good high-speed aircraft configuration tested in Ref. 12, which is plotted on the figure, the pilot rating is computed to change from satisfactory to acceptable. This change is in agreement with the pilot ratings presented in Ref. 12, where the rating changed from 3 to 5 with the addition of the actuator dynamics.

Applications

It has been shown in the preceding section that the closed-loop system characteristics and the defined levels of pilot response can be used to determine pilot ratings for longitudinal aircraft control. The pilot rating will be determined if the specified closed-loop characteristics can be achieved with

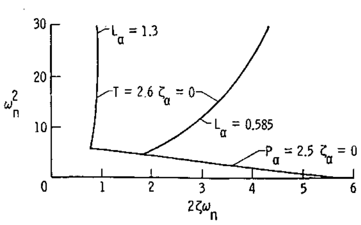


Fig. 9 Comparison of attitude control with first-level pilot model for two values of L_α.

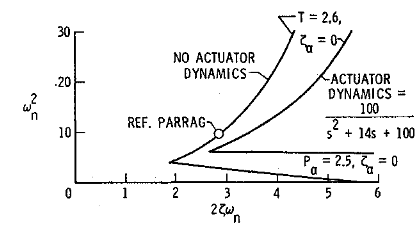


Fig. 10 Effect of actuator dynamics on calculated system response boundaries.

either the first-level pilot response, thereby determining that the aircraft will be rated satisfactory; or the second-level pilot response, thereby determining that the aircraft will be rated acceptable.

It is expected that the same procedure can be used to determine lateral handling qualities, or the handling qualities of helicopters. Since single-loop variable closed-loop characteristics have consistently shown that a 2-sec time characteristic is a required and desired value, it is expected to hold true for other vehicles and other modes of motion. It may be necessary to allow some adjustment of the outer-loop variable response to correspond to the performance that pilots have come to expect with different vehicles. The value to use can be determined by correlating with previous pilot rating data, as was done in the present investigation.

Conclusions

System response characteristics obtained using pilot models have been shown to correlate with pilot ratings in the following items: 1) in the shape of the boundaries in the airplane short-period $\omega_n^2 - 2\zeta\omega$ plots; 2) in the change in pilot ratings with change in L_α; and 3) in the change in pilot ratings with the insertion of control actuator dynamics. It is therefore concluded that a prediction of pilot ratings can be made by determining the level of response of the pilot required to achieve specified system characteristics.

This method can also be used to compare competing designs and to provide a rational engineering interpretation to pilot comments.

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Summary and Interpretation of Recent Longitudinal Flying Qualities Results

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Recently obtained longitudinal flying qualities data[1–4] are interpreted and analyzed with respect to their similarities, differences, relevance to particular tasks, and agreement or disagreement with other task-related results. In general, the recent data fall into line with and extend other, older results. Certain of these extensions re-emphasize the importance of spatial as well as time response characteristics for good terminal-area flying qualities.

Introduction

IT is the author's purpose to try to consolidate the results of four recent papers[1–4] with respect to each other and to the literature in general. This consolidation and explanation role is a kind of self-imposed one that we at Systems Technology, Inc. (STI) have assumed over the years. Some of the resulting "explanations" may not stand the test of time, especially if the data involved are fragmentary or diverse, but they at least provide some timely food for thought pertinent to the next round of experiments. Naturally such thought-provoking analysis involves a number of us at STI; the authors would like therefore to acknowledge the particular contributions of S. Craig and R. Heffley to the present efforts.

To begin with, we will spend considerable time analyzing the A'Harrah, Lockenour data and the results thereof will tie in fairly directly with Bihrle's results. The Miller and Eney data are somewhat separate, but the former are shown to be consistent with the A'Harrah, Lockenour data; the latter are related to other similar results.

A'Harrah, Lockenour's Results

The setup utilized in the Ref. 1 investigation was rather unique in that independent variations in $1/T_{\theta_2}$, n_{z_α}, and CAP† were simulated by 1) assuming blended (variable) control of wing and fuselage incidence to provide an effective direct (wing) lift control (DLC) component geared to the elevator/stick motions and 2) using a large range in approach air speeds while maintaining constant (displayed) closing speed. With respect to the first artifice, we should note additionally that the simulation setup did not provide the pilot with angle-of-attack information on either the wing or the fuselage. Therefore it appears that he could have had no real appreciation for how the lift was being generated except, of course, his awareness of *attitude* changes and the corresponding changes in flight path (discussed more fully below). His main point of reference being an attitude change, he would probably be more interested in lift due to attitude than in lift due to an "artificial" α which he could not see. We expected, therefore, that n_{z_α} as "artificially" changed by the elevator/wing gearing was not, in fact, a parameter of importance to the pilot. The data tabulated in Fig. 1 reinforce this notion. Here the parameter $(n_{z_\alpha})_1$ is the gearing-modified parameter used in the Ref. 1 correlations, while n_{z_α} is the conventionally defined parameter of Eq. (1). The tabulation lists all the "raw" (pilot rating) data available to the author‡ for $1/T_{\theta_2} = 0.8$ and 0.2 for $\omega_{sp}^2 = 0.8$ and 1.6. The trends shown in this compact sample are exemplary of those exhibited by the complete set of data. We can see that the values of $(n_{z_\alpha})_1$ are not really indicative of any piloting problem or interaction. That is, wide variations in this parameter can occur without changing the pilot rating, provided the normally defined values of n_{z_α} and $1/T_{\theta_2}$ are held constant. Conversely, for constant values of $(n_{z_\alpha})_1$ and $1/T_{\theta_2}$, pilot ratings can vary between 2 and 10 as n_{z_α} changes (e.g., for $1/T_{\theta_2} = 0.8$). The conclusion we came to from these considerations was that the use of $(n_{z_\alpha})_1$ to correlate the Ref. 1 data was probably not valid. We therefore concentrated our examination of the data to considerations of the normally computed value of n_{z_α} given by

$$n_{z_\alpha} \equiv (U_o/g)(1/T_{\theta_2}) \tag{1}$$

The second interesting simulated effect noted previously was the maintenance of constant closure speed for a wide range in effective airspeeds as measured, for example, by the value of n_{z_α} defined previously. Closed-loop analyses (e.g., Ref. 8) and detailed observation of piloting behavior[11] indicate

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† Bihrle's "Control Anticipation Parameter"; see discussion under Altitude Control Comparisons.

‡ Obtained from notes on a briefing given by the Ref. 1 authors, Jan. 17, 1969. Some of these raw data points are not apparent in the correlations presented in Ref. 1.