VTOL Control System Studies on a Six-degree-of-freedom Motion Simulator

RICHARD K. GREIF, EMMET B. FRY,
RONALD M. GERDES, and
TERRENCE D. GOSSETT
Ames Research Center, NASA, Moffett Field, California, U.S.A.

SUMMARY

VTOL control concepts, with and without stabilisation, were optimised and compared on a six-degree-of-freedom motion simulator. Features of this simulator and its suitability for VTOL research are discussed. Results are presented to show which control concepts provide the best handling qualities and require the least control power, both in calm air and in the presence of random disturbances. Discussion includes a brief treatment of non-linear concepts and system failure effects.

1. INTRODUCTION

A critical item in the design of VTOL aircraft is the provision for control in hover and low-speed flight. Because dynamic pressures are too low during these operations to permit the use of aerodynamic control surfaces, control must be derived from the propulsion system of the vehicle itself. Most VTOL propulsion concepts, however, are very sensitive to added burdens of any kind, and the amount of control required in hover usually results in a direct trade-off with performance. Needless to say, the designers of these vehicles are therefore interested in establishing minimum acceptable levels of control power for both normal and emergency flight conditions(1). Anything more might seriously limit the utility of the vehicle, while anything less would compromise safety.

An equally important aspect of low-speed flight is the lack of any aero-dyanamic stability. Little is known, however, regarding the way in which this factor should be taken into account in control system design. Just as the control system provides control for the pilot, it can also be used to stabilise the aircraft. The increased cost and complexity of such an approach must be weighed against potential improvements in handling qualities and/or potential reductions in control power.

VTOL aircraft in the past have used various schemes to deal with the stability problem in hover. As an example of the simplest approach, the Hawker-Siddeley P1127 has been flying successfully since 1960 without relying on any means other than inherent aerodynamic damping to prevent attitude divergence. Aircraft such as the Balzac and Mirage IIIV have taken a somewhat more complicated approach by incorporating artificial rate damping to protect against excessive rate build-up. As an example of yet more complexity, the VJ–101C aircraft uses artificial methods to stabilise both rate and attitude in the hovering mode.

Although considerable experience has been gained from these aircraft and others like them, it has been difficult to determine just which control system concepts are most efficient in terms of handling qualities and control power requirements. In an effort to answer this question, the NASA Ames Research Center has included in its overall VTOL research programme a series of experiments to investigate a variety of low-speed control system concepts. This work is being done on an advanced simulator capable of large motions in all six degrees of freedom. It is the purpose of this paper to describe this equipment and to discuss current results on the comparison of control concepts.

SYMBOLS

I_x	roll moment of inertia, lb ft sec^2 (or slug ft^2)
L	rolling moment, lb ft
L_δ	roll control gain, lb ft/in; L_δ/I_x control sensitivity, rad/sec^2/in
L_p	roll rate feedback gain, lb ft sec/rad; L_p/I_x rate damping, 1/sec
L_ϕ	roll attitude feedback gain, lb ft/rad; L_ϕ/I_x attitude feedback, 1/sec^2
p	body-axis roll rate, rad/sec
PR	pilot rating
SR	saturation ratio
ss	steady state
δ	control displacement, in.
ζ	damping ratio, damping/critical damping
ϕ	Euler angle roll attitude, rad
$\dfrac{\phi_{ss}}{\delta}$	bank angle sensitivity, rad/in
ω_n	undamped natural frequency, rad/sec ($\omega_N=\sqrt{(L_\phi/I_x)}$)

2. EQUIPMENT

Description of the simulator

The unique aspect of the six-degree-of-freedom simulator is its motion capability. Other simulators have been built with various combinations of motion and degrees of freedom, but the six-degree-of-freedom simulator is believed to be the only device in current operation with large motion capabilities about all six degrees. In its present configuration (Fig. 1), the simulator is restricted to visual hovering tasks, but future plans call for the addition of moving artificial visual displays in order to simulate transition and forward flight. With this arrangement, the visual display will provide the large displacement cues, such as that due to forward speed, while the simulator motion will provide the short-period perturbations about the steady-state case.

Visual scene. In simulating the visual hovering task, artificial displays are purposely avoided. Instead, large doors in front of the simulator are opened to provide the pilot with an actual outdoor scene. This relatively simple feature has resulted in a surprising degree of realism. The scene, of course, is fixed (hence the restriction to hover tasks), but it has none of the problems of colour, resolution, and third dimension associated with artificial displays. In addition, its open-air effect causes pilots to be less concerned about the

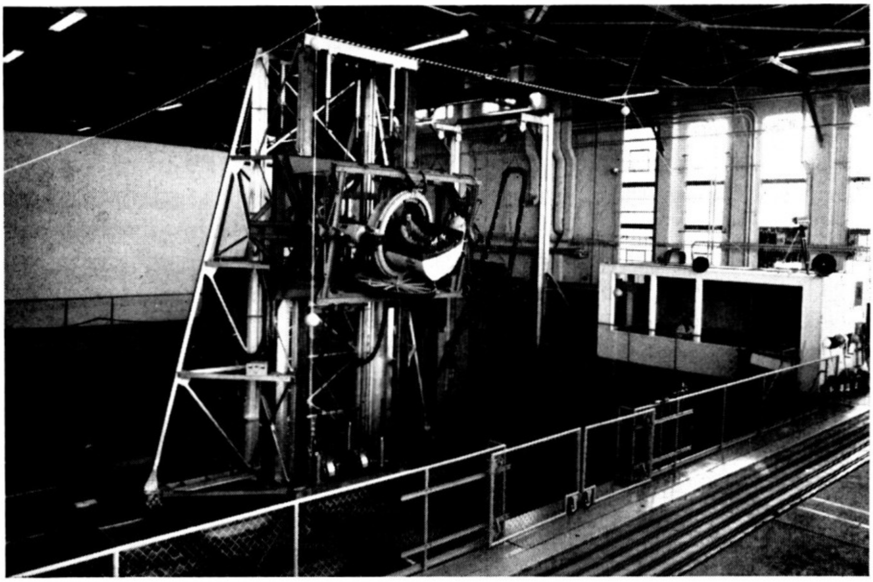


FIG. 1 — Ames six-degree-of-freedom simulator

falseness of 'indoor flight'. Admittedly, the importance of these environmental effects has long been debatable, yet the fact remains that the confidence level of simulator results has consistently been degraded by the extent to which pilots must extrapolate to imagine the actual flight case. Any attempt, then, to reduce the artificialities of a simulation will generally prove worthwhile in the achievement of useful results.

Motion capabilities. The travel envelope of the simulator is described by rotational limits of $\pm 45^\circ$ in roll, pitch and yaw, with translational limits of ± 9 feet in the longitudinal, lateral and vertical directions. Angular acceleration limits are all greater than $6\ \mathrm{rad/sec^2}$. Linear acceleration limits are $7\ \mathrm{ft/sec^2}$ horizontally, and $10\ \mathrm{ft/sec^2}$ vertically.

Of the foregoing, only the horizontal travel limits (and to some extent the horizontal acceleration limits) have been somewhat restrictive. However, experience has shown that the general hovering task with reasonably large manoeuvres can be investigated without difficulty, and, very important, without resorting to motion washout techniques. All motions therefore occur just as they would in actual flight.

The simulator is powered by electric motors used in Ward–Leonard type servo systems. Silent chains transmit power to the angular modes, while cables transfer power to the linear modes. The overall system operates smoothly, has good frequency response, and is described by pilots to be very effective in reproducing the important sensations of hovering flight.

Some effects of motion

The degree to which motion contributes to the validity of simulator results is difficult to discuss in general terms. Previous treatment of this subject(2,3) has indicated that the necessity for motion cues is dictated more often by the particular, rather than the general, aspects of a given flight situation. In other words, examination of a general flight task may indicate the absence of significant motion for all but a particular part of that task in which motions or accelerations may be the pilot's predominant cue. The real problem here is to determine under what circumstances a pilot will respond primarily to either visual cues or motion cues, or a combination of both.

Experience with the six-degree-of-freedom simulator has shown that motion cues can be extremely important to the simulation of VTOL hovering tasks. Again, the value of motion becomes apparent only in particular instances, for the general hovering task is primarily one in which pilots respond to visual cues. Those instances where motion was felt to be essential have been experienced in at least four separate situations. One example occurred during control system studies in which undesirable short-period pilot-induced oscillations were often critical to system evaluations. These oscillations were of the type which are generally suppressed beyond recognition in a visual display. Another example occurred during similar studies, this time involving systems which were sometimes characterised by large phase lags between pilot input and aircraft response. Attempts to assess identical situations in simulators without motion required extremely dangerous phase lags before the pilot became aware of their presence. A third instance concerned studies of pilot response to failures, such as a sudden loss of a lift-engine or a stability augmentation system. In simulations without motion these situations were frequently indicated to be more severe than they really were, simply because corrective actions were unnecessarily delayed upon visual recognition of the problem. When motion was present, corrective actions were taken in response to the acceleration effects of the failure, rather than the lagging visual effects. As a result, corrections were quicker, displacements were less, and recovery was often no problem. The fourth example was encountered during tests of a lateral acceleration device for VTOL applications. A critical factor in the tailoring of this system was the amount of lateral acceleration the pilot could comfortably tolerate. Obviously, non-moving simulators cannot reproduce situations in which pilot comfort is a factor, nor for that matter, any situation in which pilot-vehicle dynamic coupling is involved.

While motion is essential in instances such as those described in the preceding paragraph, it should not be concluded that meaningful results cannot be obtained from non-moving simulators. When used for comparative type studies, these devices are extremely useful. However, the question of whether their results are conservative or optimistic will eventually become a matter of concern. Unfortunately, the question has no simple answer, since the lack of motion can falsely aggravate a situation (as in the case of failures), or it can falsely suppress a serious problem (as in the case of phase lags or pilot-induced oscillations). To some extent, these factors can be taken into account. The extent to which they cannot, however, must be added to the burden of subsequent flight research.

Simulator validation — comparison with flight

Before using the simulator for general VTOL research, a study was made to determine how well its results might compare with those obtained in actual flight. A few results from this study are presented in Fig. 2.

The aeroplane used for comparison was the Bell X–14 jet-lift VTOL. It was equipped with a rate-damped control system in which both control power and damping could be varied$^{(4)}$. With the simulator mechanised in a nearly identical way, concurrent tests were run to evaluate various combinations of control power and damping on the basis of a nearly similar task.

The bands indicate the combinations that resulted in both a $3\frac{1}{2}$ and a $6\frac{1}{2}$ pilot rating$^{(5)}$. Good agreement between simulator and flight is apparent

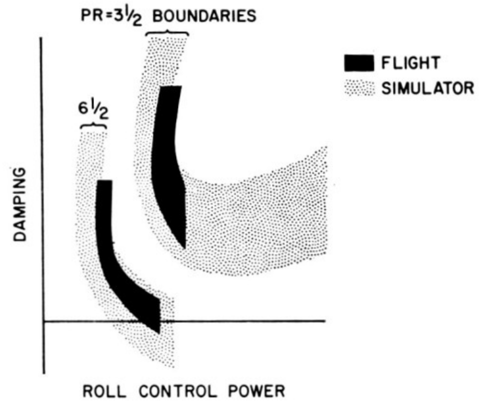


FIG. 2 — Comparison of six-degree-of-freedom simulation and flight, X–14

in both cases. This result does not mean that flight research is no longer necessary; it merely helps to substantiate earlier remarks that the simulator is capable of providing valid preliminary results, so that subsequent flight tests can be abbreviated.

3. TESTS

The control systems tests discussed in the remainder of this paper are concerned with VTOL aircraft which require attitude changes in order to translate. Such aircraft are characterised by thrust vectors fixed in relation to the aircraft, thus requiring rotation of the entire vehicle in order to generate a horizontal force.

The foregoing is illustrated in Fig. 3, along with the essential elements of the control system itself. The general objective of the study was to determine what effect various stabilisation feedback techniques and control input techniques would have on handling qualities and control power requirements. It should be noted that for simplicity in this study, aerodynamic effects were ignored; hence, the aircraft was assumed to have no inherent stabilisation.

Description of systems studied

Linear systems. The majority of the study deals with control concepts using proportional control and linear stabilisation feedback. Proportional control means simply that the output of the pilot's controller varied linearly with his input.

Three basic concepts for controlling attitude were tested and compared.

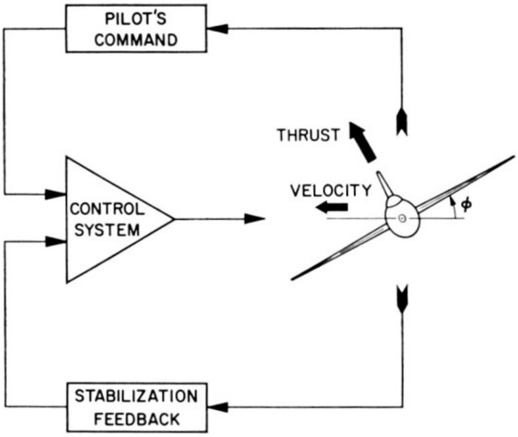


FIG. 3 — VTOL control systems using attitude change for horizontal translation

For purposes of discussion, they will be referred to as the acceleration system, the rate system, and the attitude system. The descriptive elements of each system are presented in Fig. 4.

The acceleration system has no stabilising feedbacks. As its time history shows, stick deflections produce steady-state acceleration, and the pilot must provide stability and angular-rate damping while controlling attitude. The control-system variables pertinent to this system are control power and control sensitivity.

The rate system is obtained simply by providing the acceleration system

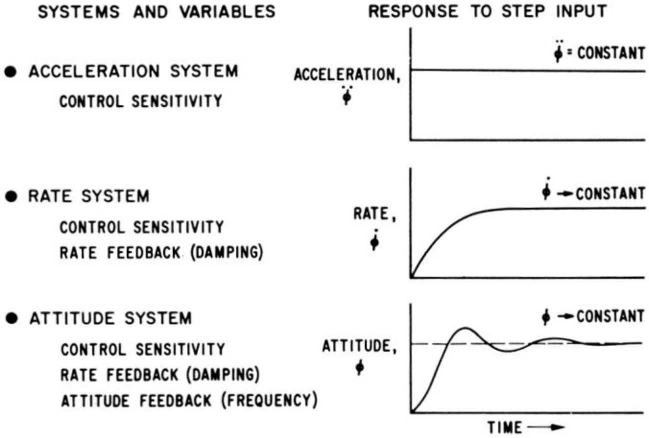


FIG. 4 — Types of systems tested
(All systems linear)

with angular-rate feedback. For this case, stick deflections produce steady-state rate. To control attitude, the pilot must provide attitude stability, but he does not have to worry about excessive rate build-up. The variables associated with the rate system are control power, control sensitivity, and damping. Damping is simply the gain in the rate feedback loop.

The attitude system goes one step beyond the rate system by incorporating attitude feedback in addition to rate feedback. For this system, pilots command steady-state attitude proportional to stick deflection, and all stabilising requirements are automatically provided. The variables which describe the attitude system are control power, control sensitivity, damping, and frequency. Frequency refers here to the undamped natural frequency of the system. It is a commonly used measure of the stability of a second-order system; more precisely, frequency is equal to the square root of the gain in the attitude feed-back loop. The actual oscillatory characteristics of an attitude system are not defined by frequency alone, but by frequency and damping together. To illustrate this, the time history shown at the bottom of Fig. 4 is typical of a somewhat under-damped case; that is, if damping were increased, the oscillations could be made to disappear.

Non-linear system. A test was also conducted to study the characteristics of a non-linear variation of the attitude system. It will be referred to as the attitude system with saturation. Very briefly, this system combined both non-proportional control and non-linear feedback in a manner such that large control inputs by the pilot had a temporary cancelling effect on the feedback signals. A more detailed explanation of this system is presented later together with a discussion of its results.

Test conditions

The conditions for the majority of the tests are shown in Fig. 5. The only exception involved a brief series of tests to evaluate the effects of random upset disturbances. As a general rule, simplicity was stressed to ensure a basic understanding of each control system before subjecting it to complex conditions. For example, rather than attempting at this stage to optimise control stick geometry and force characteristics, a representative set of values was selected and held constant throughout the tests.

For all of the test conditions, the simulator was operated in the six-degree mode. However, systematic data were generated for the roll axis only. This was done for the following reasons: first, the roll axis is usually more critical than pitch or yaw; in addition, roll-axis data should qualitatively apply to the pitch axis. From the latter standpoint, the pitch-axis parameters were varied identically with the roll-axis parameters throughout the tests. Since the yaw axis was not considered of primary concern, it was permanently maintained as a satisfactory rate system.

- Calm air (no gusts, cross-winds, or ground effect)
- Ideal systems (no actuator dynamics, etc.)
- No gyroscopics or cross-coupling
- Constant control geometry

	Maximum Control Deflection in.	*Force Gradient, lb/in.*	*Breakout Friction, lb*	
Roll	±5	1·8	1	Centre stick
Pitch	±5	1·8	1	
Yaw	±2·5	0	6	Rudder pedals
Throttle	Fighter type quadrant			

FIG. 5 — Test conditions

Three pilots, each with a diverse test background including considerable VTOL experience, participated in the test. Two of the pilots were used in all phases of the study, and the third was used for selected verification of the results. The pilots performed the same tasks and used the same method of evaluation(5).

Evaluation tasks

The simulator task was designed simply as a general hover task and a general manoeuvre task. Since the main intent was to establish a common basis for system comparison, no further attempt was made to define tasks which would be universally representative of actual flight situations. (In actuality it is now generally agreed that the VTOL task is not universal in the first place; that is, it will vary with vehicle size and mission.)

The hover task was divided into two parts: precision hovering at a point in space, and precision altitude changes to simulate take-off and landing. The manoeuvre task consisted of translation start-stops and roll reversals.

Because of their nature, the simulator tasks are believed to be more demanding than their counterparts in flight, at least for the majority of VTOL aircraft. For example, the precision hover task involved the pilot's ability to hover a given system within limits of the order of ±2 feet. It is obvious that many VTOL aircraft, though fully suitable for their own design mission, would have difficulty hovering within limits several times this amount. For the manoeuvring case, the start-stops were performed by moving rapidly from one hover point to another, separated by distances of about 15 feet.

While this might represent a realistic situation in actual flight, the existence of physical travel limits in the simulator tend to make pilots critical of errors which might be unnoticed in flight.

The foregoing was pointed out in order to emphasise the fact that the simulator results discussed in the next section are valid primarily for comparison purposes, and should not be taken in an absolute quantitative sense. Final definitions of system requirements will still depend on subsequent flight tests, where tasks can be expanded in a more realistic manner.

4. RESULTS AND DISCUSSION

The tests began with the optimisation of variables for each of the systems previously described. When this was completed, a comparison of systems was undertaken, first in calm air, followed by a brief comparison in the presence of random disturbances.

Optimisation of parameters

During the optimisation studies, control power was held constant at a relatively high value (2 rad/sec^2) in order to minimise any influence it may have had on the results. An unavoidable exception to this occurred whenever control sensitivity was less 0·4 rad/sec^2/in., since stick travel was limited to ± 5 inches.

None of the variables was found to have a strong effect on pilot rating in the area near the optimum. Optimums are therefore presented as ranges (or bands) rather than points (or lines). The width of these ranges (or bands) was arbitrarily established to include a pilot-rating increment of about $\frac{1}{4}$ to either side of the point where pilot rating was best.

Acceleration system. Figure 6 shows the variation of pilot rating over a wide range of control sensitivity, with the optimum range lying between 0·4 and 0·8 rad/sec^2/in. (It is important to recognise that the mechanical characteristics of the control stick used in these tests may not be optimum. Changes, for example, in stick force gradient, could alter these numbers somewhat.)

There are no other variables to optimise for the acceleration system. Before continuing, however, it should be noted that this type of test was used to determine optimum control sensitivity for the rate system, and later on for the attitude system. For the rate system, the test was merely repeated at various levels of constant damping. Results here served as a starting point, since the acceleration system can be considered as a rate system with zero damping.

Rate system. Figure 7 shows the effect of damping on the optimum sensitivity range for the rate system. This is indicated by a band which was drawn

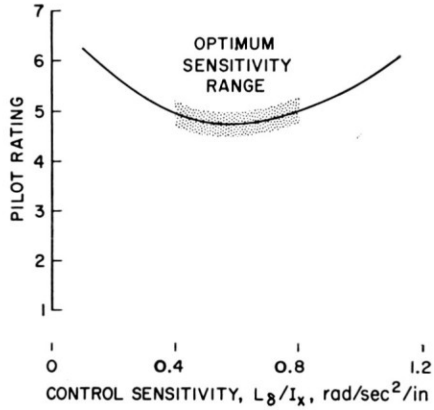


FIG. 6 — Acceleration system. Effect of control sensitivity on pilot rating

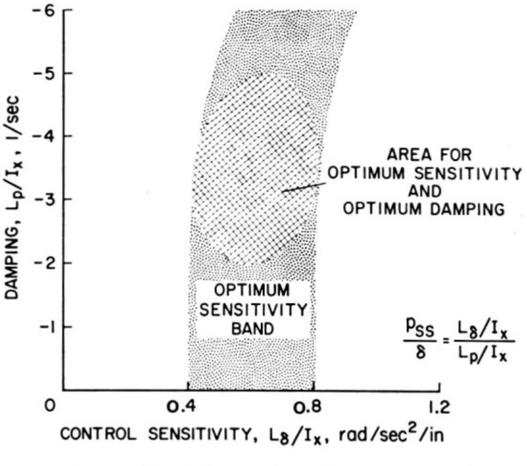


FIG. 7 — Rate systems. Variation of optimum control sensitivity with damping (including range of optimum damping)

through the optimum sensitivity ranges found at various levels of constant damping. The intercepts on the zero damping axis correspond to the acceleration system just discussed. Increasing the damping did not change the optimum sensitivity range until high damping values of about -5 1/sec were reached. Beyond that point, increases in sensitivity were required to compensate for sluggish response. Otherwise, stick motions to produce manoeuvring roll rates became uncomfortably large. (This result can be understood through study of the relationship for roll-rate sensitivity, p_{ss}/δ, shown in the figure.)

An optimum damping range for the rate system was found by examining the variation of pilot ratings along the optimum sensitivity band. For damping less than -2 1/sec, problems similar to those for the acceleration system became apparent; while for damping greater than -5 1/sec, the rate system was felt to be too 'tight' in response. Superimposing these limits on the optimum sensitivity band thus creates the optimum 'area' shown.

The optimum ranges for the rate system provide a starting point for discussion of the attitude system. In other words, the next figures will show how they vary when attitude feedback is applied.

Attitude system. Results concerning optimum control sensitivity, optimum damping, and optimum frequency for the attitude system are contained in Figs. 8, 9 and 10, respectively. To preface the discussion of these, it should be noted that sensitivity and damping were found to be interdependent variables, and the results in Figs. 8 and 9 should be interpreted accordingly. (That is, it is implicit in Fig. 8 that damping has been optimised according to its variation shown in Fig. 9, and *vice versa.*)

Figure 8 shows the variation in optimum control sensitivity with frequency. The intercepts at zero frequency correspond to the optimum sensitivity range for the rate system discussed in the preceding Figure. As frequency was increased, the optimum sensitivity values at first remained constant, and finally started to increase at frequencies above 3 rad/sec. The increase in sensitivity was required to overcome the increasing stability of the system (a situation somewhat analogous to the sluggishness of the rate system at high values of damping).

The equation shown in Fig. 8 expresses the relationship of bank-angle sensitivity to control sensitivity and frequency. (Bank-angle sensitivity is the steady-state bank angle per inch of stick deflection.) In the frequency range where optimum control sensitivity is seen to be relatively constant, optimum bank-angle sensitivity must approach infinity as frequency goes to zero. This corresponds, of course, to the fact that bank-angle sensitivity for a rate system

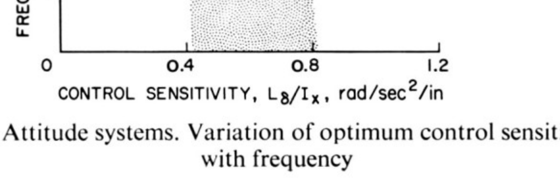


FIG. 8 — Attitude systems. Variation of optimum control sensitivity with frequency

is infinite. At high values of frequency, optimum control sensitivity is seen to increase in a manner which causes bank-angle sensitivity to approach a constant range from about 0·04 to 0·06 rad/in. For the control stick geometry used in these tests, this range could be re-expressed as from about $\frac{2}{3}^{\circ}$ to 1° of bank per degree of stick deflection. The important thing to note here is that for frequencies less than 3 rad/sec, pilots are concerned about control sensitivity, not bank-angle sensitivity. They want stick deflections to produce certain initial accelerations rather than certain steady-state bank angles. As it turns out, the desired acceleration is the same as for the two systems already discussed.

Figure 9 shows the variation of optimum damping with frequency. Once again the intercepts at zero frequency represent the values required for a rate system. It is important to note that the damping parameter used on the ordinate is the damping-to-inertia ratio, and not the familiar damping ratio, ζ, normally used to describe second-order systems of this type. Using the relationship $L_p/I_x = 2\zeta\omega_n$, values of ζ appear as lines of constant slope in Fig. 9. The curve shows that optimum damping-to-inertia ratio is relatively constant up to frequencies of about 3·0 rad/sec. This indicates that pilots are more concerned with a basic level of damping than the overshoot or undershoot characteristics which occur as a function of damping ratio ζ. For frequencies above 3·0 rad/sec, however, overshoot must be considered, and optimum damping appears to be asymptotic to a constant ζ of around 0·5.

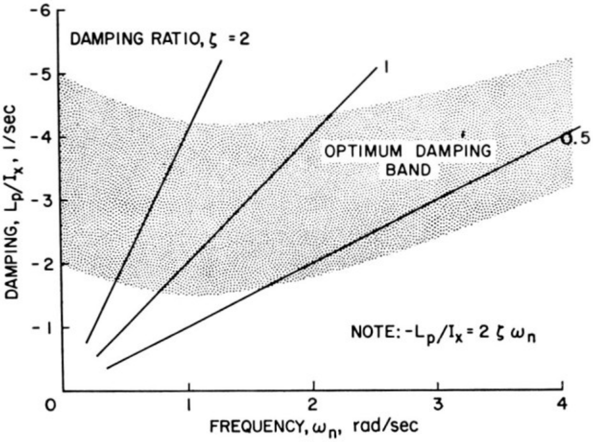


FIG. 9 — Attitude systems. Variation of optimum damping with frequency

Optimum frequency for the attitude system is shown in Fig. 10. At various levels of constant control power, pilot ratings were obtained as frequency was varied over a range from 0 to 4 rad/sec. At each frequency, control sensitivity and damping had been set at optimum values (according to Figs. 8 and 9) before evaluation. Since the steady-state bank-angle capability of a linear attitude system is equal to the ratio of maximum control power to frequency squared, it was expected that optimum frequency would decrease in some manner with control power in order to avoid bank-angle limitations. However, for control powers greater than 0·5, optimum frequency was found to lie in a constant band between 1·4 and 2·6 rad/sec. At frequencies below 1·4 rad/sec, the system was insufficiently stable, and too much pilot attention was necessary to control attitude. Above 2·6 rad/sec the system was overstable. While this effect was desirable for steady precision hovering, manoeuvring was difficult because it required large control motions. When control sensitivity was increased to improve manoeuvring, the system became oversensitive in hover. The overall effect is described by the pilots as one of excessive 'stiffness'.

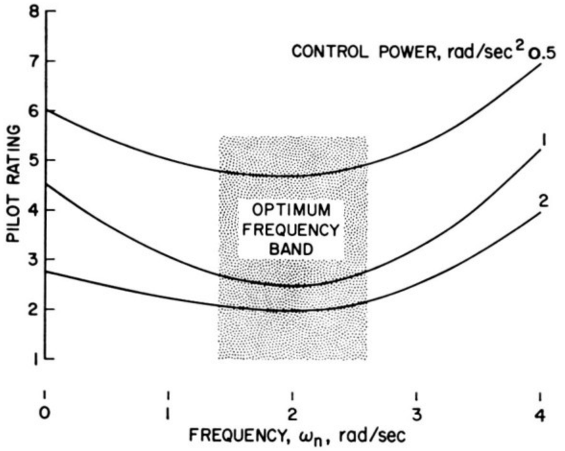


FIG. 10 — Attitude systems. Determination of optimum frequency

System comparisons

The results of the parameter optimisation studies are summarised in Fig. 11. Each of the three systems was optimised according to the mean values therein so that valid comparisons of their handling qualities and control power requirements could be made.

Comparisons in calm air. Figure 12 presents the variation of pilot rating with control power for the acceleration, rate, and attitude systems in calm air.

The acceleration system is seen to be unsatisfactory for the simulator task, regardless of control power. In essence, this system places excessive demands on the pilot's ability to perceive rates, anticipate attitudes, and then provide the proper lead time in his control inputs so that he can maintain some degree of precision. Recoveries in the event of mistakes can be accomplished if large amounts of reserve control power are available, but no amount of control power can compensate for the excessive workloads involved with this system.

● Acceleration system	
Optimum control sensitivity	0·4 to 0·8 rad/sec²/in
● Rate system	
Optimum control sensitivity	0·4 to 0·8 rad/sec²/in
Optimum damping	− 8 to − 5 1/sec
● Attitude system	
Optimum control sensitivity	0·4 to 0·8 rad/sec²/in
Optimum damping	− 2 to − 4 1/sec
Optimum frequency	1·4 to 2·6 rad/sec

FIG. 11 — Optimum parameter summary

Comparison of all three systems indicates that the progressive addition of stabilisation not only improves handling qualities, a result which was expected, but also allows significant reductions of control power. For example, the minimum control power for a satisfactory attitude system is almost 40 % less than that required for a satisfactory rate system.

If the availability of control power were no problem, it would appear from Fig. 12 that a rate system would provide nearly the same benefits as the attitude system. However, since pilots rarely give ratings better than 2, it must be

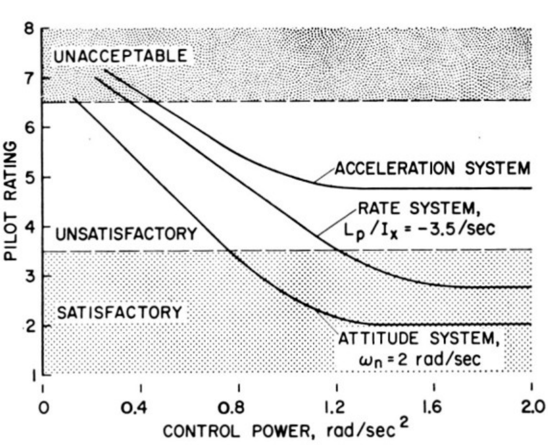


FIG. 12 — Comparison of the acceleration, rate, and attitude systems. Linear systems with all variables optimised

concluded that the attitude system has definite superiorities worth pursuing. These superiorities are reflected mainly in the hovering and precision manoeuvring tasks. Pilot comments indicate that the attitude system allows these tasks to be performed with little effort, almost in a 'hands-off' sense at times, wheres the rate system requires constant pilot attention. On the other hand, for random manoeuvring the two systems felt surprisingly alike, although the rate system was more responsive.

Effect of disturbance. It could, of course, be disastrous to provide control power sufficient only for hovering and manoeuvring in calm air. In reality, control must be powerful enough to satisfy two additional requirements: that for trim and that for controlling upsets or disturbances. This does not mean that total control power should be dictated by the simple addition of all requirements; such a conservative approach would unduly compromise efficiency. Nor does it mean that control power should be equated only to the most critical requirements. To the contrary, a practical design should account for the critical case, with some margin to allow limited operation in the others. To arrive at such a design requires information about the individual effects of all three factors.

Control required for trim depends on an aircraft's aerodynamic and mechanical configuration, and can usually be calculated or measured experimentally to a satisfactory degree of accuracy. In essence, this is a problem of statics.

The analysis of disturbance effects, on the other hand, is complicated by dynamic considerations which require knowledge of an aircraft's susceptibility to upset. Configuration is again important (in the calculation of disturbance moments), but now the aircraft size (mass and inertia) must be taken into account. Just as important is the nature of the disturbance itself. For example, the type of disturbance typically encountered in gusty air may be quite different from that due to ground effect and recirculation, and it is not always clear which is the most critical.

To obtain a preliminary understanding of disturbance effects, each of the systems in Fig. 12 was re-examined in the presence of an artificial disturbance which created random angular accelerations about the roll axis. A sample time history of this disturbance is shown in Fig. 13. Nominal frequency and peak amplitude could be varied without altering the basic wave shape. Actually, however, it was found that frequency had a relatively minor effect on pilot rating. The parameter of most significance was the ratio of peak disturbance acceleration to control power (at least for control powers between 0·8 and 2·0 rad/sec^2).

The curves of Fig. 13 illustrate the degradation in pilot rating with increasing disturbance intensity for the acceleration, rate, and attitude systems of Fig. 12. Results are also shown for a more stable attitude system with an ω_n of 4 rad/sec. The task performed to obtain these results was limited to precision hovering only; the manoeuvring task was omitted on the reasoning that a disturbance situation would force pilots to concentrate on the tasks of keeping the aircraft level and compensating for unwanted drift. By comparing intercepts and slopes of the curves, a further appreciation of the benefits of stabilisation can be obtained. The acceleration system hovers poorly in calm air and is strongly affected by disturbances. The rate system has a relatively good rating for calm air hovering and can tolerate peak disturbances of about 15% of the available control power before becoming unsatisfactory. The attitude systems exhibit not only the best calm air performance but also the lowest susceptibility to disturbance. The optimum attitude system $\omega_n =$ 2 rad/sec) has a disturbance toleration of nearly 40%, over twice that of the rate system.

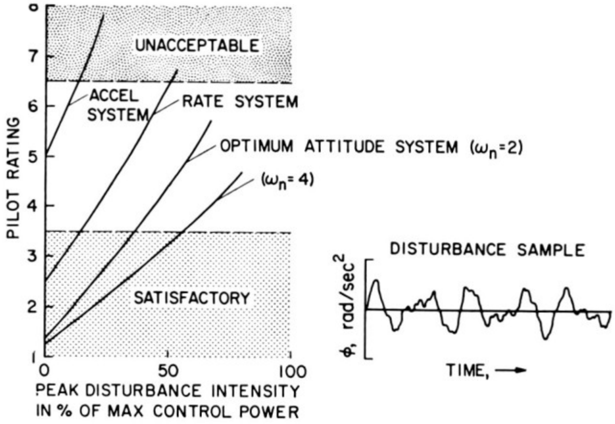


FIG. 13 — Effect of disturbance. Precision hover task

Although the disturbance toleration of the optimum attitude system appears more than adequate for practical applications, there may be instances when disturbance effects dictate an even higher degree of stability. As an indication of what some added stabilisation would provide in the way of of disturbance toleration, the curve for $\omega_n = 4$ rad/sec has been included. It should be recognised, however, that this frequency is considered impractical for linear attitude systems because of limitations previously discussed. On the other hand, non-linear designs may permit the use of higher frequencies.

It should be understood that the addition of stabilisation reduces but does not eliminate attitude displacements due to disturbances, unless of course the system is of infinite gain. Practical amounts of stabilisation, however, combined with low inherent configuration susceptibility to upsets, could result in a vehicle with no apparent sensitivity to disturbances.

System improvements

It now becomes attractive to consider possibilities for further improvement of the attitude system (in particular, to determine whether this type of system can be made to operate at lower control power levels and still retain superior handling qualities). Prerequisite to this objective is a clear understanding of all the factors which affect the control power requirements of the linear attitude system in general. These factors are summarised in Fig. 14.

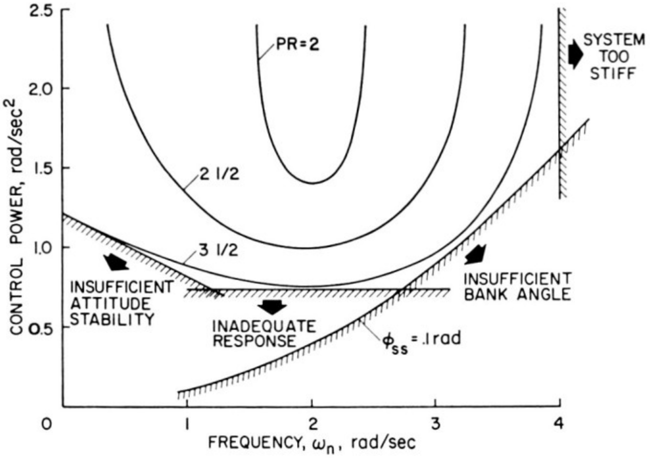


FIG. 14 — Attitude systems. Factors affecting control power requirements

Factors affecting control power of linear attitude systems. The curves of Fig. 14 show the manner in which control power requirements of linear attitude systems vary with frequency in order to maintain constant levels of handling qualities. Minimum acceptable handling qualities for satisfactory task performance are represented by a line of constant pilot rating equal to $3\frac{1}{2}$, and control powers less than those associated with this line would result in unsatisfactory systems. Also shown are lines of constant pilot rating equal to $2\frac{1}{2}$ and 2 to indicate the additional control power required to obtain increasingly superior handling qualities.

The curves appear to be shaped by the influence of four factors. As would be expected from earlier discussion, the minimum control power requirement for each curve occurs at a frequency of about 2 rad/sec. Control powers in this region are dependent primarily on manoeuvring response, or more precisely, attitude response. In other words, there is a level of control power below which attitude response is inadequate for the manoeuvring requirements of the task.

At low frequencies (less than optimum), the curves are influenced by problems of insufficient attitude stability. Because control is less precise in this region, errors are more likely to occur and extra control power is needed as a margin for their correction. Notice, however, that this statement does not completely describe the case for the curves of superior handling qualities. These curves eventually rise asymptotically to minimum levels of attitude stability, whereupon additional control power no longer has any effect. This result further illustrates the deficiency of the rate system; that is, a certain amount of attitude stability is required to avoid excessive demands upon pilot attention to the overall task.

At frequencies just above the optimum, insufficient bank angle becomes a factor. For linear attitude systems, maximum bank angle is determined by the ratio of maximum control power to frequency squared. Control power must be increased accordingly to maintain whatever bank-angle capability is required to perform a given task. Otherwise, manoeuvrability would suffer because of inadequate horizontal force generation.

At high frequencies, the attitude system eventually becomes uncomfortable to the pilot. Since system stiffness is the basic objection at this point, no amount of control power will solve the situation.

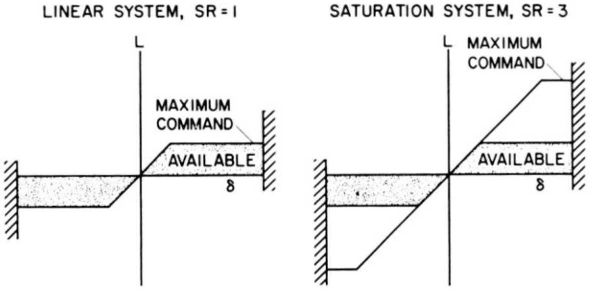
The requirement for nonlinearity. It is evident from the foregoing that control power reductions are possible only for those attitude systems in the frequency range from about 2 to 3 rad/sec. The margin for improvement, however, is limited by the extent to which the inadequate response and insufficient bank-angle problems can be overcome. Since the linear system has no further potential in either respect, it now becomes necessary to examine non-linear techniques.

Non-linear systems can be devised in a limitless variety, and the complete coverage of even a few is beyond the scope of this paper. However, the particular elements of the problem at hand suggest a general approach. First, the inadequate response problem is one which lends itself more readily to the use of non-proportional control in the pilot's stick. (An extreme case of non-proportional control was shown(6) to allow dramatic reductions in control power and may, in a modified form, be applicable here as well.) The problem of insufficient bank angle, on the other hand, suggests the use of non-linear stabilisation feedback.

In essence, the whole approach to non-linear system design is a tailoring process, and must take into account the incompatible demands of the VTOL task. In simple terms, an efficient control system must be adaptive to both the stability requirements for hovering and the response requirements for manoeuvring.

Tests of a non-linear attitude system. As part of a continuing programme to investigate non-linear control methods, tests were conducted on a relatively simple non-linear attitude system which appeared to offer a simultaneous solution to the response and bank-angle problems mentioned above. The system has sometimes been called an attitude system with saturation control, but will be referred to here as the saturation system.

Technically, the saturation system is based on the principle of providing the pilot's control with more acceleration command than is actually available in the control system itself. Diagrams comparing the saturation system with a linear system of equal control power are shown in Fig. 15. (The linear system therein is typical of a low control power system with optimised sensitivity but with relatively wide-spaced stops on control travel. This explains why the output of the control is not linear in the pure sense of the word.) With the linear system, the pilot can never command the system to produce more than its available moment (or acceleration). With the saturation system, large inputs from the pilot's control have the effect of saturating the control system at its maximum output, a condition which temporarily produces pure acceleration. Once the feedback signals become large enough to counteract the control input, the control system unsaturates and behaves just like a linear system. (In the precise sense, saturation depends on the difference between the control and feedback signals. Large, quick inputs produce saturation. Large, slow inputs do not.)



$$\text{SATURATION RATIO, SR} = \frac{\text{MAXIMUM COMMAND MOMENT}}{\text{MAXIMUM AVAILABLE MOMENT}}$$

$$\phi_{\text{MAX}} = \text{SR}\left(\frac{\text{MAXIMUM CONTROL POWER}}{\omega_n^2}\right)$$

FIG. 15 — Description of saturation control.
Moment vs. control deflection

The saturation system is attractive from three standpoints. First, it provides maximum initial response (in fact, pure acceleration) for the large, quick control inputs typical of rapid manoeuvring. Second, the system retains a constant level of static stability upon reaching any steady-state bank angle. The third advantage of the saturation system is that it provides a simple method for increasing maximum bank angle without increasing control power.

The system can be described in terms of its saturation ratio, which is simply the ratio of maximum command moment from the stick to that actually available from the control system. Note from the diagram that saturation ratio is a direct indication of bank-angle magnification. For example, a saturation system with $SR=3$ will provide a maximum bank angle three times that of a linear system ($SR=1$) with the same available control power.

Tests of the saturation system were complicated, but the important results are presented simply in Fig. 16. This shows the control power requirements for a linear attitude system and a saturation attitude system, each with a satisfactory ($3\frac{1}{2}$) pilot rating. Comparison of these curves indicates that saturation allows a relatively insignificant control power reduction of about 10%. However, saturation also results in an upward shift of optimum frequency, so that when the factors of upset are taken into account, the effective reduction might be more on the order of 15%.

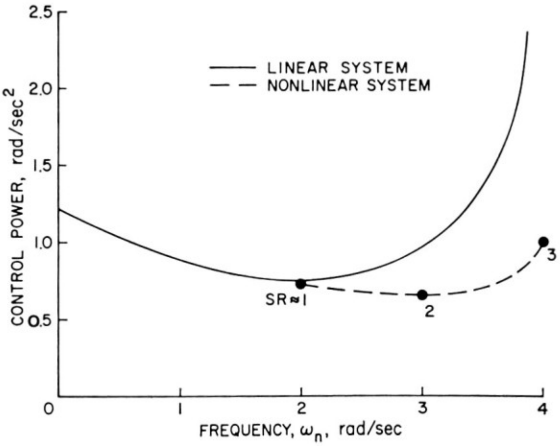


FIG. 16 — Attitude systems. Effect of saturation-type nonlinearity on control power required for $PR=3\frac{1}{2}$

The benefits of saturation result primarily from increased bank angle. (Improvements in response were relatively insignificant.) Inherent with this system, however, is a degrading phase lag characteristic between pilot input and aircraft response which is aggravated by the amount of saturation. Therefore, it is important to realise that saturation should not be used unless a bank-angle problem exists in the first place. Even then, its benefits are limited to the point where phase lag begins to dominate.

In summary, it is evident that saturation systems have potential benefits. However, the present results indicate that significant reductions in control power will depend primarily on the development of better non-linear methods of optimising response, and this may prove difficult. In any event, it is important to realise that other non-linear systems may introduce the same phase-lag dangers characteristic of the saturation system.

System failures

An undesirable feature of control system complexity is the increased possibility of failures. For this reason alone, past designs have stressed simplicity to such an extent that handling qualities have often been compromised. In modern aircraft design, handling qualities are recognised to be just as important to overall safety as control system reliability.

Figure 12 contains some interesting implications regarding failures. For example, if a satisfactory (pilot rating of $3\frac{1}{2}$) attitude system should experience a failure in its attitude feedback loop, it would revert to a rate system with a pilot rating of about 5. This is because its sensitivity and damping are essentially the same as those for the rate system shown in the same Figure. By the same reasoning, if a satisfactory attitude system lost both its feedback loops, it would revert to an acceptable (for emergency operation) acceleration system. The only case not shown here is the one for a failure of the damping loop in the attitude system. This case is undesirably oscillatory, but is nevertheless acceptable for emergency operation.

It was suspected that the transients involved in a sudden failure might overtax a pilot's ability to recognise and adapt to a degraded system in sufficient time to avoid loss of control. However, extensive tests on the simulator failed to uncover any situation where this was the case, as long as the pilot was reasonably alert to a failure possibility, and more important, as long as he was experienced in flying the degraded systems. The most dangerous cases involved abrupt transitions to either the acceleration system or the undamped attitude system. Failures requiring transition from an attitude to a rate system (loss of attitude loop) were no problem whatsoever.

5. CONCLUDING REMARKS

It was the intent of this paper to present comparative information showing how the handling qualities and control power requirements of hovering VTOL aircraft are affected by the concepts upon which their control systems are designed. The important trends are summarised in the following paragraphs.

The provision of large amounts of control power is not, in itself, a guarantee of good handling qualities. Consideration must be given to the type of control system being used, and to whether the elements comprising the system have been optimised.

Studies indicate that handling qualities can be improved and control powers reduced if control systems are designed to stabilise the aircraft as well as to provide control for the pilot. Considerations of safety alone will usually require some degree of rate stabilisation, but the most efficient systems are those which provide attitude stabilisation as well.

Attitude-stabilised systems result in superior handling qualities because they alleviate workloads on the pilot. (This was evident even in calm air conditions, but became more significant as disturbance effects were imposed.) At the same time, attitude-stabilised systems can operate at substantially reduced control power levels because they minimise inadvertent control errors and hence require lower control power margins for corrective actions. Neither of these benefits requires large amounts of stabilisation; in fact, too much stabilisation will eventually result in poor handling qualities and excessive control power requirements.

Some currently proposed VTOL configurations may not be able to meet even the comparatively low control power requirements of the linear attitude system. Studies indicate that this problem might be overcome by resorting to non-linear control system designs. However, it appears that such systems must be carefully designed, since their benefits may be accompanied by subtle, yet dangerous, degrading effects on certain areas of system behaviour.

This information was obtained from experiments on an advanced simulator capable of considerable motion in all six degrees of freedom. The motion was found to contribute significantly to the realism and, more important, to the research latitude of the simulator, making it an extremely efficient and valid tool for extensive preliminary research. Consequently, it is believed that the cost of motion will, to a large extent, be recoverable through the increased safety and simplification of subsequent flight research.

REFERENCES

(1) Anderson, Seth B., 'An Examination of Handling Qualities Criteria for V/STOL Aircraft,' NASA TN D–331, 1960.

(2) O'Hara, F., 'Prediction of Aircraft Flying Qualities by Flight Simulators and Other Methods, With Flight Comparisons,' Paper No. 64–555. Presented at Fourth ICAS Congress in Paris, France, Aug. 24–28, 1964.

(3) Sadoff, Melvin, Harper, Charles W., 'A Critical Review of Piloted Flight Simulator Research,' Presented at IAS National Speciality Meeting on the 'Man-Machine Competition' in Seattle, Wash., Aug. 10–11, 1962.

(4) Pauli, Frank A., Hegarty, Daniel M., Walsh, Thomas M., 'A System for Varying the Stability and Control of a Deflected Jet Fixed Wing VTOL Aircraft,' NASA TN D–2700, 1965.

(5) Cooper, George E., 'Understanding and Interpreting Pilot Opinion.' *Aero. Eng. Rev.*, **16,** No. 3, 47–51, 56, 1957.

(6) Garren, John F., Di Carlo, Daniel J., Driscoll, Norman R., 'Flight Investigation of an On–Off Control for V/STOL Aircraft Under Visual Conditions,' NASA TN D–3436, 1966.

DISCUSSION

Professor A. R. Collar (University of Bristol, U.K.): I was greatly impressed — as no doubt was everyone present — by the film showing the operation of all six degrees of freedom of the simulator; I was also impressed by the excellent correlation between the results from the simulator and from free flight. I believe all the results described were obtained using all six degrees of freedom. Have any results been obtained with one or more degrees of freedom suppressed, and if so, how do they correlate with flight? Such information might encourage those operating more modest apparatus.

NASA – AMES

R. K. Greif: Although we certainly share Professor Collar's concern for the validity of results from simulators with little or no motion, we have not exploited the six-degree simulator's full potential for providing quantitative answers to the question. Most of our current knowledge on the effects of motion has been obtained as a by-product of general VTOL control system studies rather than specific tests designed to establish motion requirements for valid simulations. This information is discussed on pages 1028 and 1029 of the preceding text. It may be of interest to add that the results in Fig. 2 were essentially repeatable with only the roll motion activated, provided that the pilots used the same bank angle maximums for their evaluations. There did appear to be a trend towards better agreement with flight as more degrees of motion were activated, but the over-all spread in results from all tests was practically insignificant. Whether or not these results can or even should be interpreted as encouragement for operators of modest simulation equipment is, in the writer's opinion, questionable. Situations can probably be found where even the most sophisticated simulators cannot produce results which quantitatively agree with flight. It would be foolish, therefore, to expect any simulation to define absolute design criteria for flight. It would be equally foolish, however, to overlook even the modest simulator's potential for contributing to a better understanding of handling qualities problems. The trends established by these devices are invaluable when used in the proper way — and that is to simplify and safeguard the actual flight research required to finalise design criteria.