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EFFECT OF STABILIZATION ON VTOL AIRCRAFT IN HOVERING FLIGHT

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16. Abstract

A motion simulator study was conducted to determine the effects of roll and pitch stabilization on the handling qualities and control power requirements of VTOL aircraft during hover and short-distance maneuvering flight. Three levels of stabilization complexity were compared: no stabilization, rate stabilization, and attitude stabilization. Control sensitivities and stabilization gains were optimized prior to comparison. Results are presented to show how the optimum systems were determined and how they compared with each other at different levels of control power. Comparisons were made both in calm air and in the presence of roll disturbances. Results indicate the attitude-stabilized system provides the best handling qualities for the least amount of control power.

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NOTATION

cg	center of gravity
CP	control power (control moment/moment of inertia)
g	acceleration of gravity
I_x	roll moment of inertia
I_y	pitch moment of inertia
I_z	yaw moment of inertia
L	rolling moment
L_δ	roll-control gain; $\frac{L_\delta}{I_x}$ = roll control sensitivity
L_p	roll rate feedback gain; $\frac{L_p}{I_x}$ = roll rate damping, 1/sec
L_ϕ	roll attitude feedback gain; $\frac{L_\phi}{I_x}$ = roll attitude feedback
M	pitching moment
M_δ	pitch-control gain; $\frac{M_\delta}{I_y}$ = pitch control sensitivity
M_q	pitch rate feedback gain; $\frac{M_q}{I_y}$ = pitch rate damping, 1/sec
M_θ	pitch attitude feedback gain; $\frac{M_\theta}{I_y}$ = pitch attitude feedback
N	yawing moment
N_δ	yaw-control gain; $\frac{N_\delta}{I_z}$ = yaw control sensitivity
N_r	yaw rate feedback gain; $\frac{N_r}{I_z}$ = yaw rate damping, 1/sec
p	body-axis roll rate, rad/sec
$\frac{p_{ss}}{\delta}$	roll rate sensitivity

q	body-axis pitch rate, rad/sec
$\frac{q_{ss}}{\delta}$	pitch rate sensitivity
r	body-axis yaw rate, rad/sec
PR	pilot rating
$\frac{T}{W}$	thrust-to-weight ratio
ss	steady state
u	body-axis longitudinal velocity (positive forward)
v	body-axis lateral velocity (positive right)
w	body-axis vertical velocity (positive down)
δ	control displacement
ζ	damping ratio (actual damping/critical damping)
ϕ	Euler angle roll attitude, rad
θ	Euler angle pitch attitude, rad
$\frac{\phi_{ss}}{\delta}$	bank angle sensitivity
$\frac{\theta_{ss}}{\delta}$	pitch attitude sensitivity
$\dot{( )}$	derivative with respect to time, ("DOT") $= \frac{d(\ )}{dt}$
ω_{nx}	undamped natural frequency in roll, $\sqrt{\left\lvert \frac{L_\phi}{I_x} \right\rvert}$, rad/sec
ω_{ny}	undamped natural frequency in pitch, $\sqrt{\left\lvert \frac{M_\theta}{I_y} \right\rvert}$, rad/sec

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IN HOVERING FLIGHT

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SUMMARY

A motion simulator study was conducted to determine the effects of roll and pitch stabilization on the handling qualities and control power requirements of VTOL aircraft during hover and short-distance maneuvering flight. Three levels of stabilization complexity were compared: no stabilization, rate stabilization, and attitude stabilization. Control sensitivities and stabilization gains were optimized prior to comparison. Results are presented to show how the optimum systems were determined and how they compared with each other at different levels of control power. Comparisons were made both in calm air and in the presence of roll disturbances. Results indicate the attitude-stabilized system provides the best handling qualities for the least amount of control power.

INTRODUCTION

A major complication in the design of VTOL aircraft results from the need to provide for attitude control in hover and low-speed flight. Dynamic pressures are too low during these operations for conventional aerodynamic control surfaces to be effective, so control must be derived from the powered-lift system of the vehicle itself. The problem is that most VTOL powered-lift concepts are very sensitive to added burdens of any kind, and unless the amount of control for hover is carefully selected, a costly tradeoff with performance will result. Too much control power could detract from potential performance, and too little could reduce usable performance.

An equally important aspect of hovering and low-speed flight is the lack of aerodynamic stability. As in the case of control, stabilization can also be derived from the powered-lift system, but very little systematic information exists to show how much or what kind is really necessary. There are countless possible stabilization schemes, but no scientific means to determine which is likely to produce the best handling qualities for the least cost 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 British Hawker-Siddeley P.1127 flew quite successfully in the early 1960s with nothing more than a small amount of inherent (aerodynamic) rate damping. Later versions of the P.1127 along with aircraft such as the French Balzac and Mirage

III V took a somewhat more complicated approach by incorporating artificial rate damping. As examples of yet more complexity, two German aircraft, the VJ-101C and the Dornier DO-31, employ artificial methods to stabilize both rate and attitude in the hovering mode.

Although considerable experience has been gained from these aircraft and others like them, the peculiarities of their designs and the often unique conditions under which they were flight tested have made it impossible to compare their control system concepts and arrive at any valid conclusions regarding handling qualities and control power requirements for VTOL aircraft in general. The same can be said about simulator investigations on the subject. Many have been done but enough differences can always be found in the way they were set up or conducted to question the validity of any comparisons. In an effort to create a better understanding of the subject, Ames Research Center is conducting a series of simplified experiments to investigate and compare 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. The purpose of this report is to discuss current results on the comparison of three control concepts: an acceleration (unstabilized) system, a rate-stabilized system, and an attitude-stabilized system.

The authors wish to acknowledge the extensive participation and valuable contributions of Major Joseph G. Basquez (Ret.), Edwards AFB Flight Test Operations, V/STOL Branch, as a principal research pilot in this study.

EQUIPMENT

Description of the Simulator

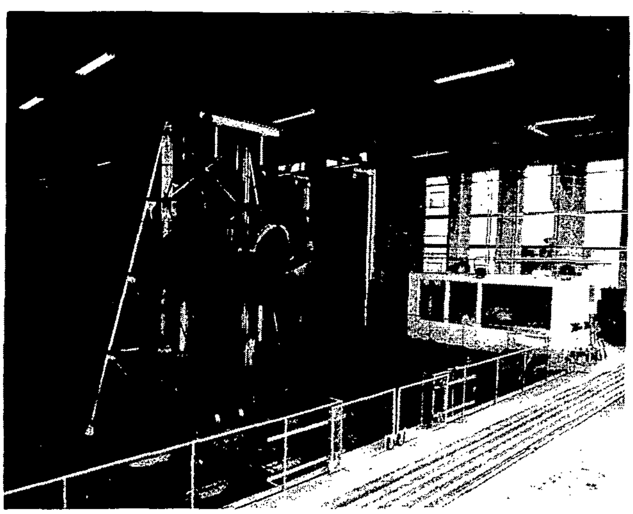


Figure 1. Ames six-degrees-of-freedom simulator.

The investigation was conducted on a six-degrees-of-freedom motion simulator (fig. 1) with all six modes operating. Reference 1 presents a description of the facility along with an evaluation of its effectiveness for simulating visual hovering tasks. Features and details pertinent to the present investigation are presented below.

Motion capabilities– The travel envelope of the simulator was described by rotational limits of ±45° in roll, pitch, and yaw, and by translational limits of ±2.7 *M*(±9 ft) in the longitudinal, lateral, and vertical directions. All angular acceleration limits were greater than 6 rad/sec^2. Linear acceleration limits were 2.1 *M*/sec^2 (7 ft/sec^2) horizontally, and 3.1 *M*/sec^2 (10 ft/sec^2) vertically. Phase lags were less than 30° at 1.5 Hz in rotation and less than 20° at 1.0 Hz in translation (ref. 1).

All motions for this study were generated at full scale without attenuation or washout of any kind. Except for the travel limits, then, the motions were equivalent to actual flight. The pilots would have preferred more horizontal travel, even though experiments have shown (ref. 1) that a general hovering task can be performed on this simulator with maneuvers large enough to produce results very close to those from flight.

Visual scene– An actual outdoor hangar-ramp scene, available by opening large doors in front of the simulator, was used throughout the investigation. This feature, made possible by the natural correspondence between full-scale motion cues and fixed visual cues, resulted in a surprisingly realistic open-air effect that helped to counteract the falseness of "indoor flight."

EXPERIMENTS

General Scope and Qualifications

The investigations were concerned with control/stabilization concepts for VTOL aircraft of the type that use attitude changes (rather than thrust-vector changes) in order to translate. The problem is one of managing the rotation of the entire vehicle in order to generate the horizontal forces necessary to maintain a hover or to maneuver at low speeds.

The foregoing is illustrated in figure 2 along with the essential elements of the control/stabilization system. The operation of the system was very simple. The pilot's control commands and the stabilization commands were summed together to produce net accelerations on the vehicle. Thus the same moment-producing device was used both for control and for stabilization. The only variables in the system were the control gains (control sensitivities), the stabilization feedback gains, and the maximum control powers from the moment generators.

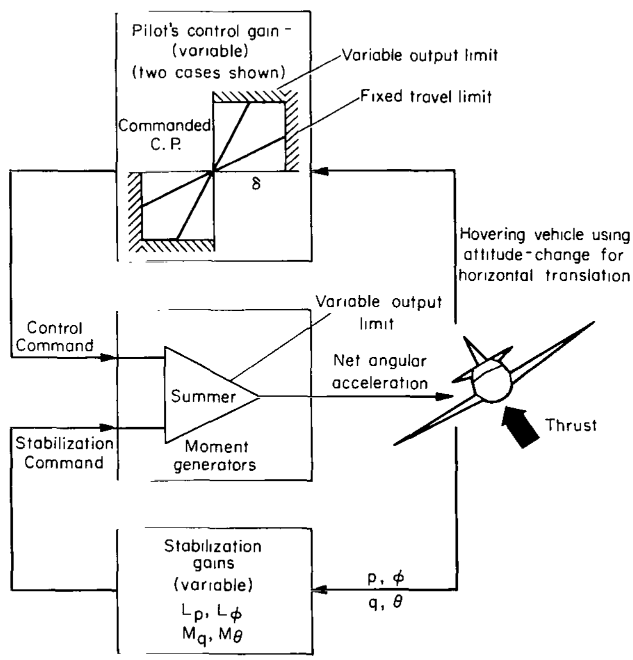


Figure 2. Schematic definition of the experiment.

It is important to note in figure 2 that variable output limits were placed on the moment generators *and* on the pilot's controls. These were always set such that the pilot could command as much as the moment generators could produce but never more. This distinction is important in the mechanization of systems in which both the control and the stabilization requirements are served by the same moment generator. If the pilots were allowed to overcommand the moment generators, they would "saturate" at their maximum output until the stabilization signals became large enough to cancel the overcommand. The effect, in the meantime, would be a pure acceleration. For the system discussed in this report, the only time a saturated condition could exist in the moment generators would be following a control reversal. Control reversals create situations where the pilot's command and the stabilization command can be temporarily additive and therefore capable of exceeding the output capability of the moment generators.

The entire control/stabilization system was linear except for a control stick nonlinearity that occurred under certain conditions as follows. The pilot's control sensitivity and his maximum control power were independently variable, but the control stick travel was fixed throughout the investigation. When maximum control power was high enough and control sensitivity low enough, the commanded control power was proportional to stick displacement all the way to the stops. But whenever maximum control power was commanded before the stick reached the stops, further displacement of the stick commanded no additional moment. The effect of this nonproportionality was not investigated. The two cases discussed are shown in the control gain diagram of figure 2.

Description of Concepts Studied

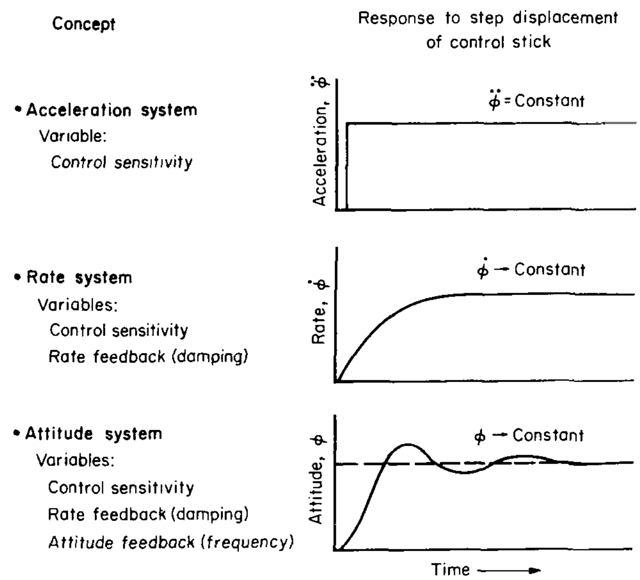


Figure 3. Types of concepts studied.

Three basic levels of stabilization feedback complexity were compared. For purposes of discussion, they will be referred to as the acceleration system, the rate system, and the attitude system. The descriptive elements and typical response-to-step-input time histories for each system are presented in figure 3.

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

The rate system is obtained by providing the acceleration system with angular-rate feedback. Its steady-state response is a constant angular rate proportional to stick deflection. To control attitude, the pilot must provide attitude stability, but he can rely on the feedback to help prevent excessive rates. 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 is obtained by providing the rate system with attitude feedback. Its steady-state response is a constant attitude proportional to stick deflection. The variables that describe the attitude system are control power, control sensitivity, damping, and frequency. In this report frequency refers to the undamped natural frequency of the attitude system. It is a commonly used measure of the stiffness of a second-order system and can be determined by taking the square root of the gain in the attitude feedback 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 figure 3 is typical of a somewhat underdamped case; that is, if damping were sufficiently increased, the oscillations would not occur.

Equations of Motion

The equations of motion did not include aerodynamic terms of any kind (hence the simulated aircraft had no inherent stability). Product-of-inertia terms were neglected and small-angle assumptions were made on roll and pitch attitudes. The inertia terms were chosen so that $I_x : I_y : I_z = 1{:}2{:}3$. The resulting equations were:

$$
\begin{aligned}
\dot{p} &= \overbrace{\left(\frac{L_\delta}{I_x}\right)}^{\substack{\text{Pilot's}\\ \text{command}}} \delta + \overbrace{\left(\frac{L_p}{I_x}\right) p + \left(\frac{L_\phi}{I_x}\right) \phi}^{\substack{\text{Stabilization}\\ \text{feedback}}} - \overbrace{\left(\frac{I_z - I_y}{I_x}\right) qr}^{\substack{\text{Inertia}\\ \text{terms}}} \\
\dot{q} &= \left(\frac{M_\delta}{I_y}\right) \delta + \left(\frac{M_q}{I_y}\right) q + \left(\frac{M_\theta}{I_y}\right) \theta - \left(\frac{I_x - I_z}{I_y}\right) rp \\
\dot{r} &= \left(\frac{N_\delta}{I_z}\right) \delta + \left(\frac{N_r}{I_z}\right) r - \left(\frac{I_y - I_x}{I_z}\right) pq
\end{aligned}
$$

Note: For positive damping and attitude stability, the terms $\frac{L_p}{I_x}$, $\frac{M_q}{I_y}$, $\frac{N_r}{I_z}$, $\frac{L_\phi}{I_x}$, & $\frac{M_\theta}{I_y}$ are *negative.*

$$
\begin{aligned}
\dot{u} &= -g\theta + rv - qw \\
\dot{v} &= g\phi + pw - ru \\
\dot{w} &= -\left(\frac{T}{W} - 1\right) g + qu - pv
\end{aligned}
$$

Study Conditions

The conditions for most of the study are given in figure 4. Simplicity was stressed to ensure a basic understanding of all concepts and to provide an unconfused basis for their comparison.

The simulator was operated in the six-degrees mode throughout the investigation, but the investigation itself was concerned only with the roll and pitch modes. Roll control systems were studied first, and during the evaluation of each particular set of roll parameters, the pitch control system was set up with the same parameters having the same values. Subsequently, when pitch control systems were evaluated, the roll control system was always set up to match the pitch system. The yaw control system, on the other hand, was permanently maintained as a satisfactory

- Pilot located at c.g. (center of rotation)
- Calm air (no gusts, crosswinds, or ground effect)
- Ideal systems (no lags, hysteresis, etc.)
- No gyroscopics
- No control cross-coupling
- Constant control geometry (shown in the table below)

	Maximum control deflection		Force gradient		Breakout friction	
	cm	in	N/cm	lb/in	N	lb
Roll*	±12.7	±5	3.2	1.8	4.4	1
Pitch*	±12.7	±5	3.2	1.8	4.4	1
Yaw**	±6.4	±2.5	0	0	26.7	6
Vertical	Left-hand quadrant type throttle					

*44.5 cm (17.5 in) center stick; all measurements made at top of B-8 type grip

**Foot pedals

Figure 4. Study conditions.

rate system. The height control system was the equivalent of a vertical acceleration system operating through a small (¼ sec) time lag to approximate engine response characteristics.

Three pilots, each with a diverse test background including considerable VTOL experience, participated in the study. The test program required approximately 800 individual evaluations. Most of these were furnished by two of the pilots; the third pilot concentrated on verification of selected results. The pilots performed the same tasks and used the same method of evaluation (ref. 2). Note that the pilot was located at the *cg* of the vehicle for this study. This was done for simplicity only. In almost any real vehicle, the pilot would be displaced from the *cg* and would therefore experience tangential motions every time the vehicle rotated.

Evaluation Tasks

The simulator task was designed simply as a general hovering task and a short-distance maneuvering task. The main intent was to establish a common basis for system comparison, so no attempt was made to define tasks that would universally represent actual flight situations. (That would probably have been impossible, since the VTOL task is expected to vary considerably with vehicle size and mission.)

The hover task involved a brief period of precision hovering at a point in space and some precision altitude changes to simulate takeoff and landing. The maneuver task consisted of fairly rapid (3.0 *M*/sec max (10 ft/sec max)) translation start-stops of about 4.6 *M* (15 ft) and roll reversals of pilot-selected frequency and amplitude to sort out possible oscillatory problems.

The tasks performed on the simulator were probably more demanding than those that would ordinarily be attempted in flight, at least for the majority of VTOL aircraft. For example, the precision hover task required an attempt to hover within limits on the order of ±0.6 *M* (2 ft). Many VTOL aircraft, though quite adequate for their own design mission, could not be hovered with that kind of precision. For the maneuvering case, the start-stops were performed by moving rapidly from one hover point to another between the edges of simulator travel. This might represent a realistic situation in actual flight, but the spectre of physical travel limits (even though harmless) in the simulator seemed to make pilots critical of errors that might go unnoticed in flight.

The foregoing was pointed out to emphasize 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 still depend on subsequent flight tests, where tasks can be expanded in a more realistic way.

RESULTS AND DISCUSSION

The tests began with the optimization of parameters for each of the systems previously described. The optimized systems were then compared in calm air and later in the presence of roll disturbances.

Optimization of Parameters

During this part of the investigation, maximum available control power was held constant at a relatively high value (2 rad/sec^2) in order to minimize any influence it may have had on the results. An unavoidable exception to this occurred whenever control sensitivity was less than 0.16 rad/sec^2/cm (0.4 rad/sec^2/in.), since stick travel was limited to ±13 cm (±5 in.).

Pilot ratings were used during this portion of the study, but only in a relative sense as a means to define the optimums. Absolute pilot rating numbers had no real meaning at this stage because control power was so high. To avoid confusion then, rating numbers have been omitted whenever possible in all figures related to the optimization studies.

None of the parameters had a very strong effect on pilot rating in the area near the optimum, so the optimum values are 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 ¼ to either side of the point where pilot rating was best.

Acceleration system— Figure 5 shows the variation of pilot rating over a wide range of control sensitivities in roll and pitch. The optimum ranges (defined above)

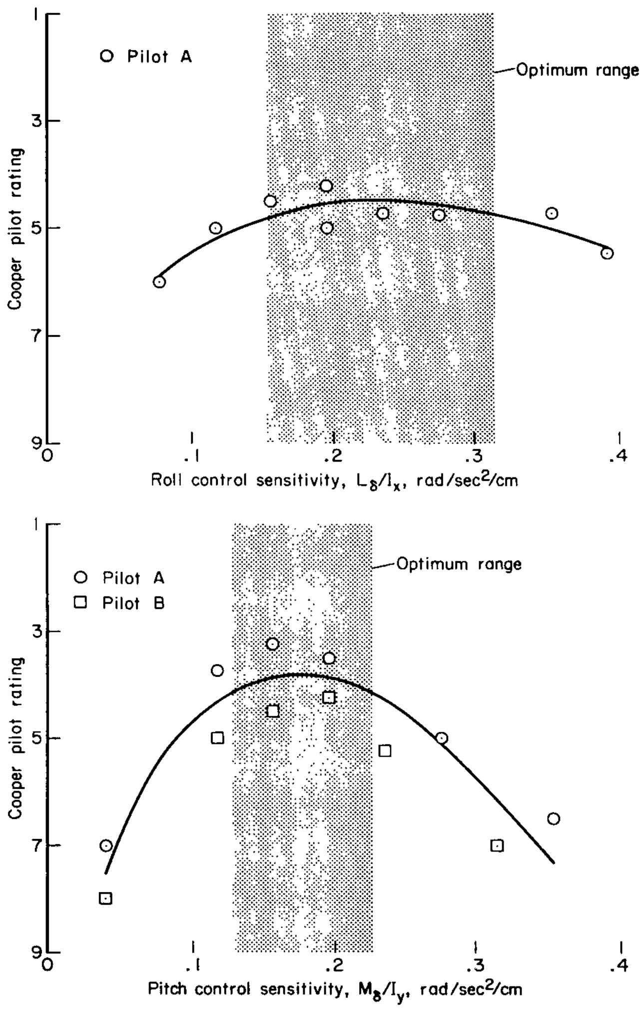


Figure 5. Acceleration system – optimum control sensitivity.

lie between 0.16 and 0.32 rad/sec^2/cm. (0.4 and 0.8 rad/sec^2/in.) for roll and 0.12 and 0.23 rad/sec^2/cm. (0.33 and 0.58 rad/sec^2/in.) for pitch.[1] Values less than optimum were desirable for steady hover but required too much stick travel for maneuvering. At values greater than optimum, maneuvering was easier but hovering became touchy.

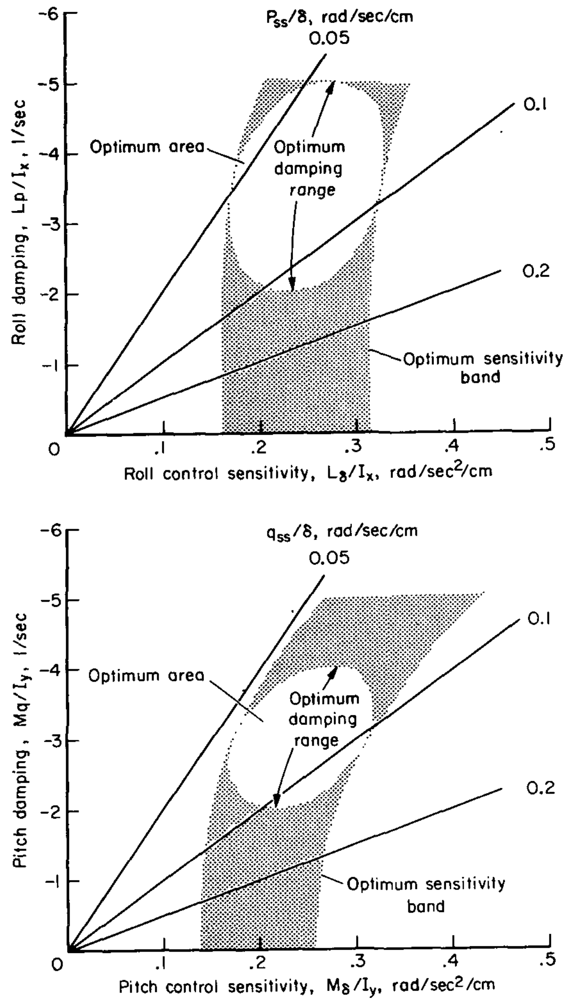


Figure 6. Rate systems – optimum control sensitivity and damping.

Rate system– Figure 6 shows the effect of damping on the optimum sensitivity ranges for the rate system. This is indicated by bands faired through the optimum sensitivity ranges at various levels of constant damping. (See footnote 1.) The intercepts on the zero damping axis would correspond exactly to the acceleration system just discussed, except for the fairing process. Increasing the damping did not appreciably change the optimum sensitivity range until high damping values of about –5/sec in roll and –3/sec in pitch were reached. Above those values, higher levels of sensitivity were needed to compensate for sluggish response. This caused problems of jerkiness for small high-frequency control inputs (worse in roll than pitch); however, without an increase in sensitivity, the stick motions to produce the angular rates required for maneuvering became uncomfortably large. The straight lines from the origin of figure 6 are lines of constant angular-rate sensitivity determined by taking the ratio of control sensitivity to damping. From the shape of the bands, it appears that pilots want steady-state angular-rate sensitivities of at least 0.04 rad/sec/cm. (0.1 rad/sec/in.) in roll and 0.06 rad/sec/cm. (0.15 rad/sec/in.) in pitch.

[1] There are no other variables to optimize for the acceleration system. Note, however, 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 same 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. For the attitude system, the same group of tests used to optimize the rate system was simply repeated at various levels of constant attitude feedback.

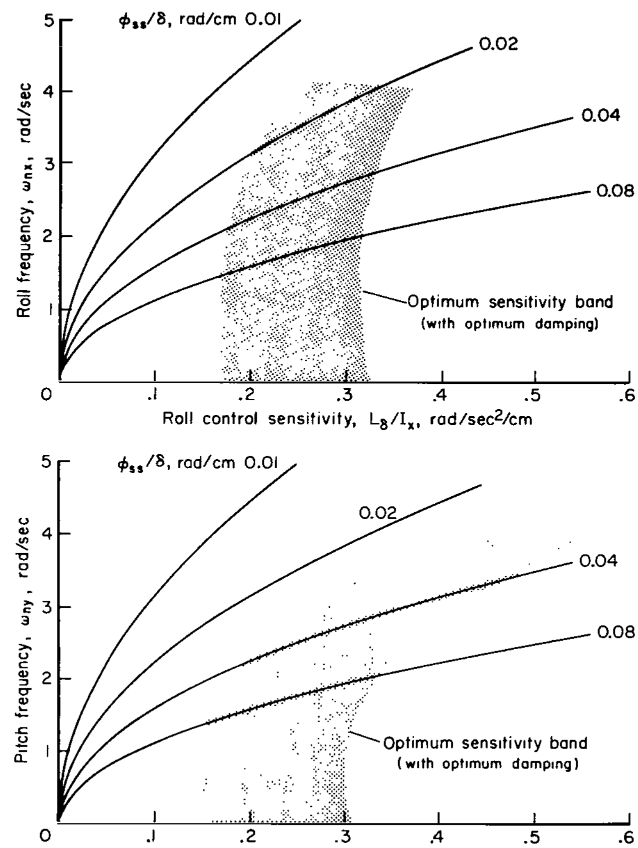
The data in figure 5 also serve to typify the scatter in the data throughout the study. The data for roll were taken in a random sequence and show roughly the consistency involved with a given pilot's ratings. The data for pitch were taken in a progressive sequence and serve more to show the discrepancies between pilots.

An optimum damping range for the rate system was found by examining the variation of pilot ratings along the middle of the optimum sensitivity band. For damping less than –2/sec in both roll and pitch, problems (described later) similar to those for the acceleration system became apparent. For damping greater than –5/sec in roll and –4/sec in pitch, the rate system was considered to be overly "tight" in response. Superimposing these optimum damping limits on the optimum sensitivity bands creates the egg-shaped optimum "areas" shown in the figure. Inside these areas, pilot rating does not vary more than about a quarter from the optimum.

The optimum ranges for the rate system provide the starting point for the attitude system since the rate system can be considered as an attitude system with zero frequency. The next figures will show how the optimum ranges vary when attitude feedback is applied.

Attitude system— Results showing optimum control sensitivity, optimum damping, and optimum frequency for the attitude system are contained in figures 7(a), 7(b), and 7(c), respectively. Before these figures are discussed, note that sensitivity and damping were found to be interdependent variables, and the results in figures 7(a) and 7(b) should be interpreted with the understanding that in figure 7(a), damping is optimum according to its variation shown in figure 7(b), and in figure 7(b), control sensitivity is optimum according to its variation in figure 7(a).

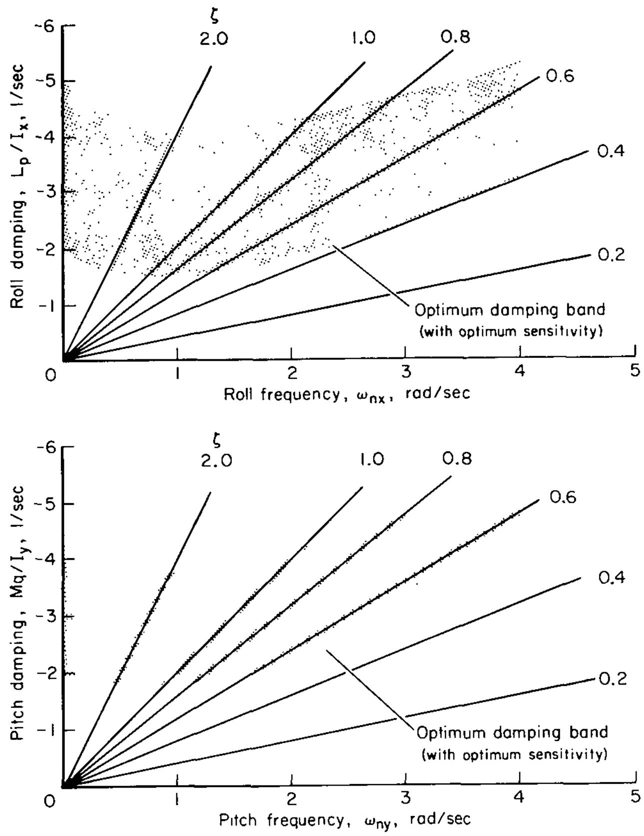
Figure 7(a) shows the variation in optimum control sensitivity with frequency. The intercepts at zero frequency correspond to the optimum sensitivity range for the rate system discussed in the preceding figure. As frequency was increased, the optimum sensitivity ranges remained fairly constant until frequencies of about 3 rad/sec in roll and 2 rad/sec in pitch were reached. Thereafter, increases in sensitivity were 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).



(a) Optimum control sensitivity.

Figure 7. Attitude systems.

The ratio of control sensitivity to frequency squared determines the attitude sensitivity (steady-state bank or pitch angle per unit of stick deflection) of an attitude system. Curves of constant attitude sensitivity have been included in figure 7(a) to help explain the shape of the optimum control sensitivity bands. In the frequency range where optimum control sensitivity is seen to be relatively constant, optimum attitude sensitivity must approach infinity as frequency goes to zero. This corresponds, of course, to the fact that attitude sensitivity for a rate system is infinite. At high values of frequency, optimum control sensitivity is seen to increase in a manner that causes attitude sensitivity to approach a constant. The important thing to note here is that for low frequencies (less than 2 or 3 rad/sec), pilots are concerned about control sensitivity, not attitude sensitivity. They want stick deflections to produce certain initial accelerations rather than certain steady-state attitudes, and it turns out that the desired accelerations for the attitude system are essentially the same as for the rate and acceleration systems already discussed.



(b) Optimum damping.

Figure 7. Continued.

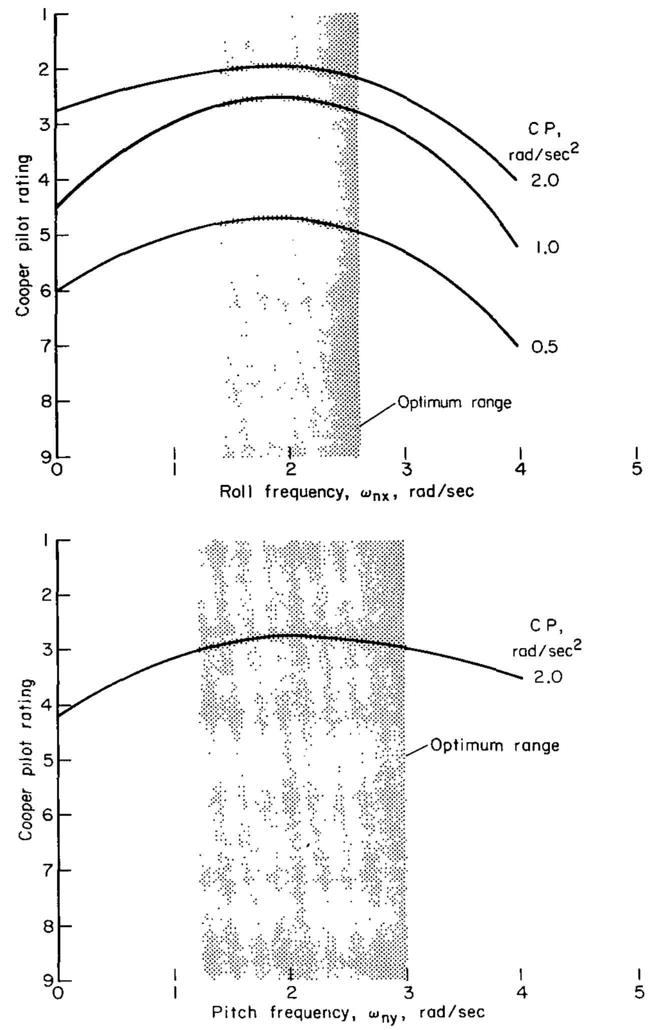
Figure 7(b) shows the variation of optimum damping with frequency. Once again note that the intercepts at zero frequency represent the values required for a rate system. It is important to note that the damping parameter used on the ordinate is the damping-to-inertia ratio, and not the familiar damping ratio ζ normally used to describe second-order systems of this type. From the relationships $L_p/I_x = 2\zeta\omega_{nx}$ and $M_q/I_y = 2\zeta\omega_{ny}$ values of ζ are represented by radial lines of constant slope in figure 7(b). The results show that optimum damping-to-inertia ratio is relatively constant with frequency up to frequencies of about 3.0 rad/sec in roll and 2.0 rad/sec in pitch. This indicates that pilots are more concerned with a basic level of damping than with the overshoot or undershoot characteristics which occur as a function of damping ratio ζ. For greater frequencies, however, overshoot must be considered, and optimum damping appears to be asymptotic to a constant ζ of around 0.5 for both roll and pitch.

Optimum frequency for the attitude system is shown in figure 7(c). At various levels of constant roll control power and at one level of constant pitch 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 figures 7(a) and 7(b)) prior to evaluation. Since the steady-state attitude 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 restrictions in maximum attitude. However, for the three control powers investigated in roll, optimum frequency was found to lie in a constant band between 1.4 and 2.6 rad/sec. Assuming the same independence on control power for the pitch case, its optimum frequency band lies between 1.2 and 3.0 rad/sec. At frequencies below the optimum range, the system was insufficiently stable, and too much pilot attention was necessary to control attitude. Above the optimum range the system was too stable. While this effect was desirable for steady precision hovering, maneuvering was made difficult by the need for large control motions. When control sensitivity was increased to improve maneuvering, the system became overly sensitive in hover. The overall effect was described by the pilots as one of excessive "stiffness."

Concept Comparisons

The results of the parameter optimization studies were used to optimize each of the three concepts so that a proper comparison could be made of their handling qualities and control power requirements. The values used for optimization were taken at the approximate center of the optimum ranges shown in figures 5, 6, and 7. (Actually, the values were chosen before the data were refined and therefore do not correspond to the exact centers of every optimum range. However, in most cases they are very close to the center and in all cases they are within the optimum range, or within a quarter of a pilot rating from the center.)

Comparison in calm air– Figure 8 presents the variation of pilot rating with control power for each of the optimized control concepts during operation in calm air. The handling qualities of all concepts, both in roll and in pitch, were strongly affected by control power, but only in the range from zero to about 1.2 rad/sec^2. Control powers higher than that had no effect on handling qualities, either because they were unneeded or because they were unusable for the simulator task. For purposes of discussion the concepts are compared in terms of: (1) the minimum control power required to produce satisfactory (*PR* = 3½) handling qualities, and (2) the best handling qualities possible at unrestricted levels of control power.



(c) Optimum frequency
(with optimum sensitivity and damping).

Figure 7. Concluded.

The acceleration system (shown only for the roll case) is seen to be unsatisfactory for the simulator task at any level of control power. Pilots appreciated the responsiveness of this system, but complained about the constant attention required to hover and the high workloads imposed during maneuvers. The hover problem is due to the absence of stability, which forces the pilot to continually cancel a tendency to diverge. Maneuvering is difficult because the pilot must manipulate acceleration in order to change attitude, a task which not only has phasing problems but involves

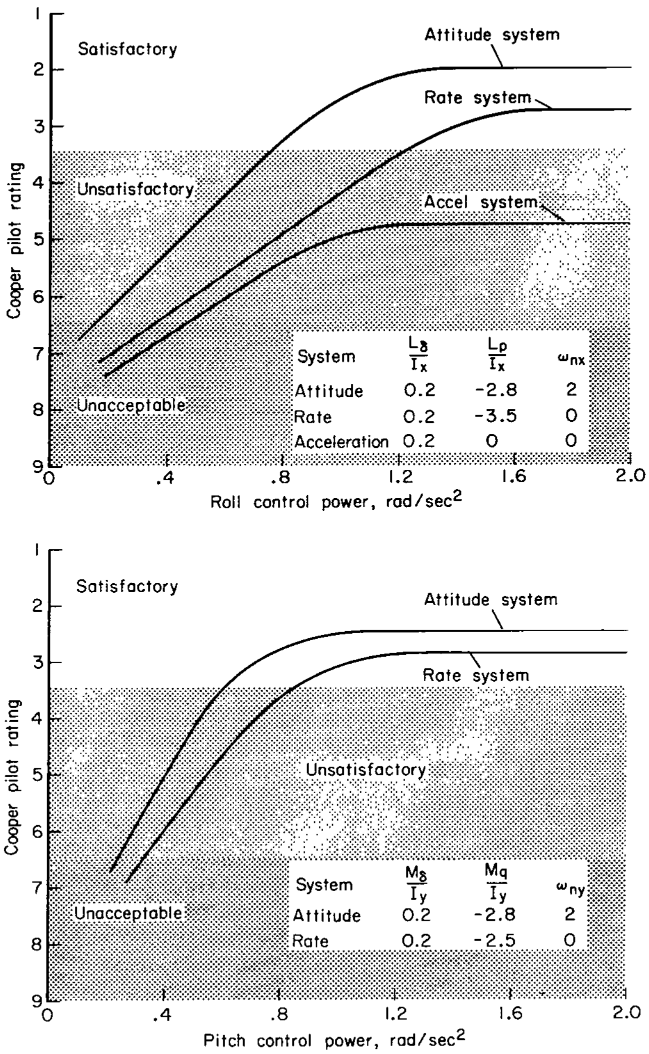


Figure 8. Comparison of optimized systems.

the pilot in a tiring process of control and countercontrol. Distractions during either phase of flight usually result in offsets and overshoots. Most of these can be recovered from if the system has enough control power, but since no amount of control power can compensate for the constant workload of the acceleration system, it never achieves a satisfactory rating.

Comparison of all three systems indicates that the progressive addition of stabilization not only improves handling qualities, an expected result, but also allows significant reductions of control power. For example, in roll, the minimum control power for a satisfactory attitude system is almost 40 percent less than that required for a satisfactory rate system. In pitch, the reduction is almost 30 percent.

If the availability of control power were no problem, it would appear from figure 8 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 concluded that the attitude system has definite superiorities. These superiorities are reflected mainly in the hovering and precision maneuvering tasks. Pilot comments indicate that the attitude system allows these tasks to be performed with very little effort, almost in a "hands-off" sense at times, whereas the rate system requires constant pilot attention. On the other hand, for random maneuvering where the pilot is continually applying control, the two systems felt surprisingly alike, although the rate system was somewhat more responsive.

Effect of disturbances– The discussion to this point has concerned results pertaining to the calm air situation with no external disturbances of any kind. To establish realistic design criteria, disturbance effects must somehow be included, but a generalized treatment of them is complicated by considerations that require specific knowledge about each particular aircraft's static and dynamic susceptibility to upset. The actual forces and moments produced by a given disturbance will vary with each configuration, and the corresponding accelerations will vary with size (mass and inertia). Equally complicated (and important) is the nature of the disturbance itself. For example, the type of disturbance created by gusty air may be quite different from that due to ground effect and recirculation. Since it is not always clear which will be the most critical, both should be investigated. The development of a disturbance model or models to do this has not yet been accomplished, so researchers must work with simplified disturbance models that will hopefully include all possible disturbance conditions.

To obtain a preliminary understanding of disturbance effects, each system in figure 8 was re-examined in the presence of a simplified artificial disturbance which imposed angular accelerations in a controlled but seemingly random manner about the roll axis. A description of this disturbance is given in the appendix along with a discussion of some results which indicated that its maximum strength (peak amplitude) had a much stronger effect on handling qualities than did its frequency, and that the effect of disturbance strength correlated on the basis of a parameter expressing the ratio of peak disturbance acceleration to maximum control power.

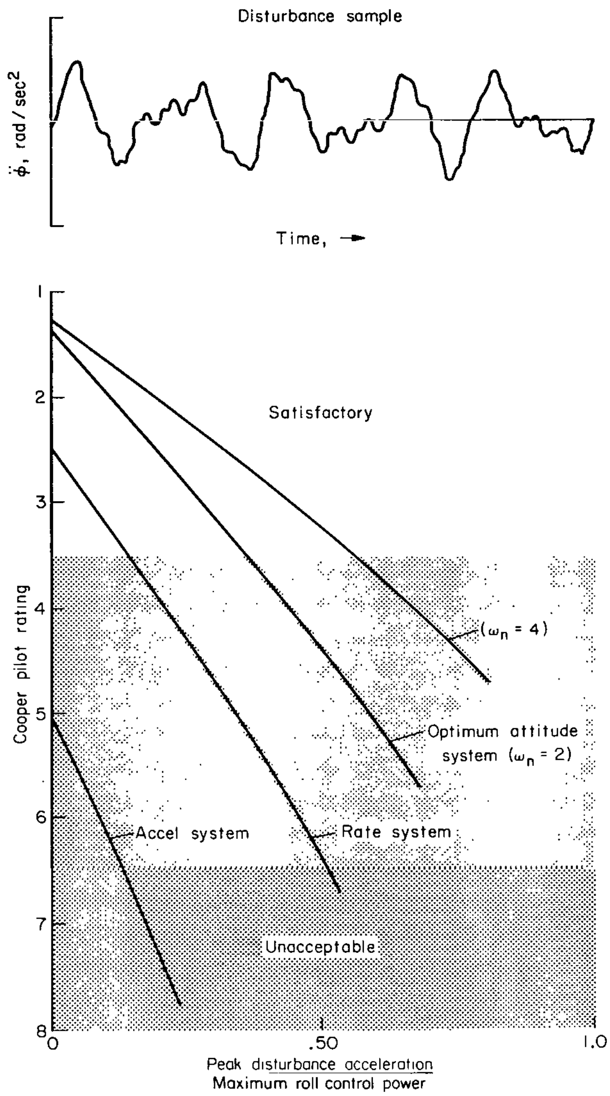


Figure 9. Effect of roll disturbances for a precision hover task.

The curves of figure 9 illustrate the degradation in pilot rating with increasing disturbance strength for the acceleration, rate, and attitude systems of figure 8. (Results are also shown, and discussed below, 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 maneuvering 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. The intercepts of the curves in figure 9 substantiate earlier statements about the desirability of stabilization in hover. The slopes of the curves reinforce them. The acceleration system hovers worst in calm air and is the most strongly affected by disturbances. The rate system has a relatively good rating for calm air hovering and can tolerate peak disturbances of about 15 percent of the available control power before becoming unsatisfactory. The attitude systems exhibit not only the best calm air performance but also the lowest sensitivity to disturbance. The optimum attitude system (ω_n = 2 rad/sec) is satisfactory up to peak disturbances of nearly 40-percent maximum control power, over twice that of the rate system.

Although the disturbance resistance of the optimum attitude system (which is really rather weakly stabilized) appears more than adequate for practical applications, there may be instances when disturbance effects dictate a higher level of stability. As an indication of what could be expected from extra stabilization, the curve for $\omega_n = 4$ rad/sec has been included in figure 9. It shows superior performance for this particular hovering task, but to use such a system for all hovering and maneuvering operations would require some way to overcome its previously discussed limitations. This serves to illustrate a fundamental incompatibility in the requirements for the control and stabilization of VTOL aircraft. Pilots want maximum response to their own inputs and minimum response to all others. The linear response–feedback type system cannot differentiate between the two. The alternatives are to tailor the pilot inputs and the stabilization feedbacks in nonlinear ways or to decouple the control system in a manner that would permit response transfer functions to pilot inputs and external inputs to be adjusted independently. Both are subjects beyond the scope of this report. Nonlinear systems are mentioned briefly in a later section, and decoupled systems of the type sometimes referred to as "model-following systems" are treated in reference 3.

Attitude System Control Power Reductions

It is attractive to look for ways of making the attitude system operate at lower control power levels and still retain superior handling qualities. This requires a clear understanding of all the factors which affect its control power requirements in the first place. These factors are summarized in figure 10.

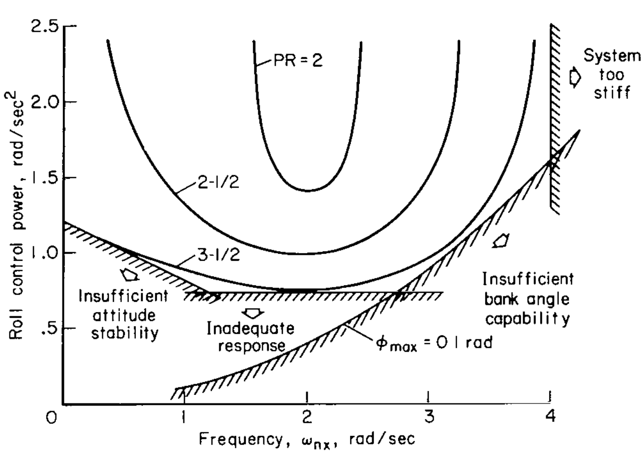


Figure 10. Attitude systems – factors affecting control power requirements.

Factors affecting control power of linear attitude systems– The curves of figure 10 show the manner in which control power requirements of a linear attitude system must vary with frequency in order to maintain constant levels of handling qualities. The analysis was done for the roll axis, but the reasoning which follows should apply to the pitch axis as well.

Minimum acceptable handling qualities for satisfactory task performance are represented by a line of constant pilot rating equal to 3½, 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 2½ 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 depend primarily on maneuvering response, or more precisely, attitude response. In other words, there is a level of control power below which attitude response is inadequate for the maneuvering 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, maneuverability 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 help 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 becomes necessary to examine nonlinear techniques. Nonlinear systems can be devised in a limitless variety, and the coverage of even a few is beyond the scope of this report. However, the elements of the problem suggest a general approach. First, the inadequate response problem is one which lends itself to the use of nonproportional control in the pilot's stick. (An extreme case of nonproportional control was shown in reference 4 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 nonlinear stabilization feedback.

In essence, the approach to nonlinear system design is a tailoring process that must take into account the incompatible demands of the VTOL task. As stated earlier, an efficient control system must be adaptive to both the stability requirements for hovering and the response requirements for maneuvering.

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 recognized to be just as important to overall safety as control system reliability.

Figure 8 contains some interesting implications regarding failures. For example, if a satisfactory (pilot rating of 3½) 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 was found to be undesirably oscillatory, but nevertheless acceptable for emergency operation.

It was suspected that the transients involved in a sudden failure might overtax a pilot's ability to recognize 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.

CONCLUDING REMARKS

It was the intent of this report to present comparative information showing how the handling qualities and control power requirements of hovering VTOL aircraft can be affected by the concepts used to control and stabilize roll and pitch attitude. Three concepts, representing a logical order of increasing complexity, were optimized and compared in the same simulator, using the same pilots doing identical tasks under common conditions. The most important trends found in this study are summarized as follows.

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

2. Handling qualities can be improved and control power reduced if control systems are designed to stabilize the vehicle as well as to provide control for the pilot. Safety alone will usually dictate angular-rate stabilization, but the most efficient systems provide attitude stabilization as well.

3. Attitude-stabilized systems result in superior handling qualities because they greatly reduce workloads on the pilot, especially in the presence of disturbances. Equally important, attitude-stabilized systems can operate at substantially reduced control power levels because they minimize inadvertent control errors and hence require lower control power margins for corrective actions. Neither of these benefits requires large amounts of stabilization; in fact, too much stabilization will eventually result in poor handling qualities and excessive control power requirements.

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Moffett Field, Calif. 94035, April 14, 1972

APPENDIX

DISTURBANCE SIMULATION

The disturbance study was very brief and was designed to obtain a preliminary idea of the sensitivity of different control/stabilization concepts to extraneous accelerations.

Disturbance Model

Four sine waves were summed together to form a random disturbance which was imposed directly as a roll acceleration on the vehicle. No attempt was made to duplicate any actual turbulence and no modes other than roll were disturbed. The objective was simply to create a random wave whose frequency content and peak amplitude could be easily controlled. A sample of the result is shown in figure 11 together with the four sine waves comprising it. Sine wave frequencies were related by the expression:

$$\text{Frequency, } \omega_i = \omega_{\text{nominal}} \left(\frac{(\pi)^{i-1}}{i}\right) \qquad i = 1,2,3,4$$

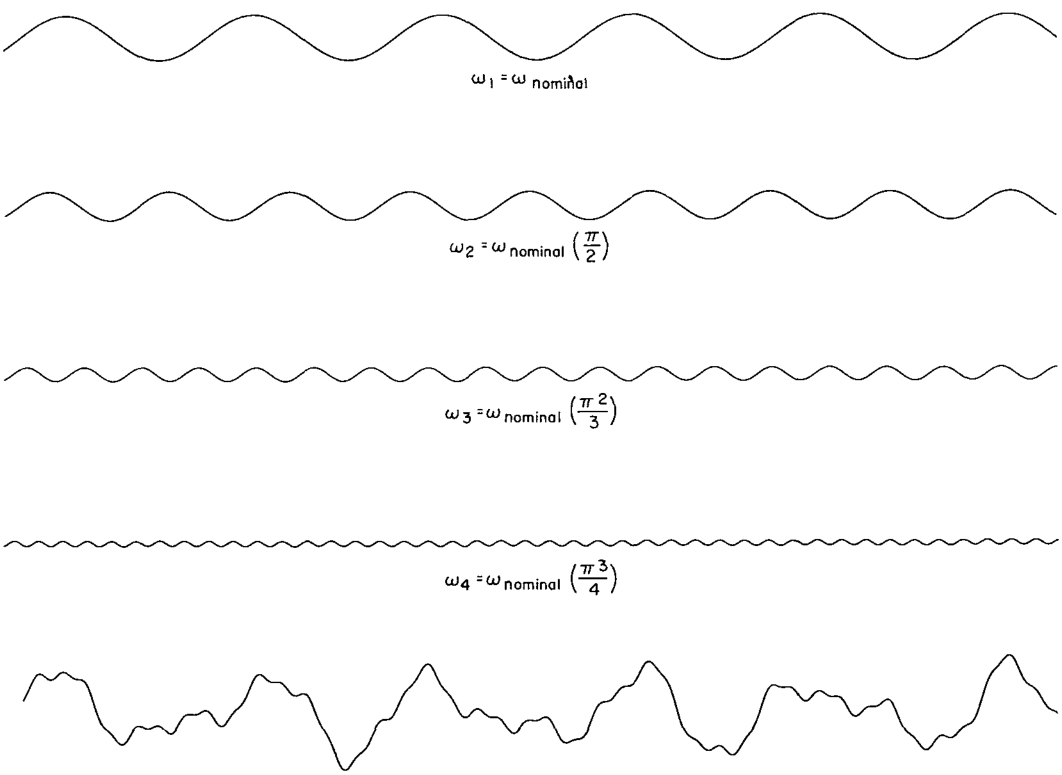

Figure 11. Generation of the disturbance model.

This was a completely arbitrary expression designed to provide an essentially random (truly random in theory) wave with a reasonable spread in frequency content. An arbitrary relationship was also chosen to set amplitudes, as follows:

$$\text{Amplitude, } A_i = A_{\text{nominal}} \left(\frac{\omega_{\text{nominal}}}{\omega_i}\right) \qquad i = 1,2,3,4$$

Maximum possible amplitude of the disturbance model was simply the sum of the individual sine wave amplitudes, and this was called "peak disturbance strength" for purposes of discussion.

Effect of Nominal Frequency

Figure 12 shows the effect of nominal disturbance frequency on pilot rating for an attitude-stabilized system with 0.8 rad/sec² maximum control power. Peak disturbance strength was held constant at 0.32 rad/sec² (0.4 times the maximum roll control power). The data show very little effect of frequency, and since similar results were obtained for the rate-stabilized system, the remainder of the disturbance study was conducted at a constant nominal frequency of 0.2π rad/sec.

Effect of Amplitude

The effect of peak disturbance strength was determined for three levels of maximum roll control power, again using an attitude-stabilized system. Nominal disturbance frequency was 0.2π rad/sec. The results, shown in figure 13, indicate that the effect of disturbance strength can be correlated on the basis of the ratio of peak disturbance strength to maximum control power, at least within the range of control power from 0.8 to 2.0 rad/sec². The disturbance strength ratio was therefore used as a variable for the rest of the disturbance study.

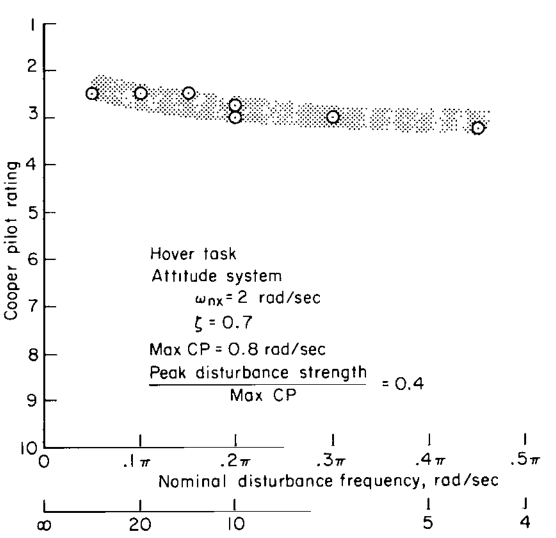

Figure 12. Effect of disturbance frequency on pilot rating.

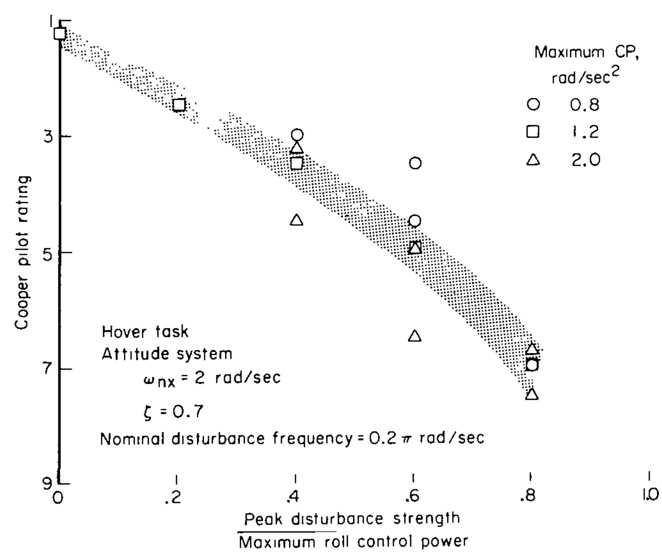

Figure 13. Correlation of pilot rating with disturbance strength ratio.

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