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ATTITUDE CONTROL REQUIREMENTS FOR HOVERING DETERMINED THROUGH THE USE OF A PILOTED SIMULATOR

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INTRODUCTION

The success of the VTOL airplane relies on the design of a safe and efficient vehicle with desirable handling qualities.

References 1 and 2 discuss VTOL handling qualities criteria with regard to providing desirable control characteristics in the hovering phase of VTOL flight. The purpose of this paper is to present the results of a simulator study conducted at the Ames Research Center for determining attitude control requirements for hovering, and to show that requirements obtained from simulator studies may be applied as criteria for flight.

Three NASA research pilots, with experience in hovering VTOL aircraft, participated in the simulator tests.

The results will be discussed in terms of control power and damping requirements for attitude control about all three axes: pitch, roll, and yaw. These requirements do not include the control necessary for trim while hovering, but represent the control required for maneuvering. Vertical translation or "height control" was not investigated.

Control requirements were first obtained about each axis separately, while the other two axes were held fixed. This allowed the pilot to devote his full attention to one control at a time. Next, the effect of controlling two axes simultaneously was determined by allowing freedom of motion about combinations of two axes, for example, the pitch and yaw axes. The reason for studying the controllability of two axes simultaneously is to show that the control requirements become more restrictive when multiple axes must be controlled, more nearly duplicating the actual hovering condition where simultaneous control of all axes is required.

Gyroscopic coupling was introduced that would result from mounting engines longitudinally, producing a couple between the pitch and yaw freedom of motion.

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EQUIPMENT

The equipment used for the tests was the Ames two-degree-of-freedom motion simulator shown in figure 1. In this configuration, the cockpit was made to rotate about the pitch and yaw axes. Various arrangements of the cockpit drive system produced angular motions about any two axes simultaneously. A more detailed description of the drive system and performance of the simulator is given in reference 3. An instrument display of airplane attitude supplemented the visible outside world in the form of a gyro-horizon for pitch and roll attitude and a radio compass indicator for heading information. Analog computer equipment computed the proper airplane dynamic responses to drive the simulator and actuate the instrument presentation. The controls used in the cockpit had linear characteristics in that the variations of control power and control force with deflection were both linear. Additional mechanical characteristics of the control system are presented in table I.

TESTS

For a generalized "first look" at the attitude control requirements for hovering, the test conditions and scope were simplified, and are shown in table II. Although disturbances from gust and ground effects were not included as quantitative inputs to the simulator, since they constitute disturbances to the airplane which vary with different airplane configurations and VTOL concepts, the pilots included these effects qualitatively in making their evaluations. Visual flight conditions were assumed throughout the evaluation. Artificial attitude stabilization was not considered.

An effective means for evaluating hovering controllability was to require the pilot to make changes of attitude as rapidly as possible, without sacrificing ability to stabilize quickly on a desired attitude. Rapid changes in attitude are often required to maneuver over or around a point while hovering. In this study the attitude changes amounted to maximums of about 15° in pitch or roll and 30° in yaw. A 15° change of attitude in pitch or roll is equivalent to a change of forward or side acceleration of about $\frac{1}{4}g$. These are felt to be realistic accelerations for use in hovering maneuvers. The magnitude of the heading changes was indicated by Ames pilots to be representative for hovering and low-speed flight.

When controlling two axes simultaneously, attitude changes were made about one axis at a time, while attempting to maintain the other axis fixed.

RESULTS AND DISCUSSION

Single Axis

The results of the single-axis evaluation are presented first for the pitch degree of freedom in figure 2. The maximum control power is the pitching acceleration obtained with maximum control deflection. The area of negative damping corresponds to divergent airplane responses to control inputs.

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In order to map the control boundaries shown, the Cooper Pilot Opinion Rating System was used, which is described in table III. (See ref. 4 for more complete description.) It is composed of rating numbers from 1 to 10 where a rating of 1 represents ideal characteristics and a rating of 10, catastrophic characteristics. A numerical rating of $3\frac{1}{2}$ represents the boundary between satisfactory and unsatisfactory regions and a rating of $6\frac{1}{2}$, the boundary separating the unsatisfactory and unacceptable regions. (See table III.) A reasonable interpretation of these boundaries is that the control system of a VTOL airplane must be designed so as to fall within this satisfactory area regardless of the amount of artificial augmentation devices necessary. However, failure of the augmentation devices must not result in a control system that falls outside of the unsatisfactory, into the unacceptable, region.

The line of optimum ratio, shown passing through the middle of the satisfactory area in figure 2, separates two regions for which there were different reasons for downgrading of pilot ratings. The test values to the right of the optimum ratio resulted in excessive control sensitivities, which caused overcontrolling of the airplane. The test values to the left of the optimum ratio represented insufficient control power, inasmuch as the responses were felt sluggish. Therefore, the optimum ratio indicates the best amount of control power for a given level of damping, and vice versa.

The roll and yaw control boundaries are shown in figures 3 and 4 with damping and control power coordinates similar to the previous figure. Again, note the regions that are satisfactory, unsatisfactory, and unacceptable. As in the evaluation of pitch controllability, pilot comments defined the existence of the line of optimum ratio for roll and yaw, shown passing through the satisfactory regions.

A plot of the pitch, roll, and yaw boundaries that are between the satisfactory and unsatisfactory regions $\left(\text{numerical rating of } 3\frac{1}{2}\right)$ is presented in figure 5 in order to compare the relative magnitudes and shapes of the boundaries for the three axes. Notice the similarity between the boundaries for the roll and yaw axes. Both of these boundaries enclose roughly the same satisfactory region, and neither boundary extends down into the negative-damping area. The pitch axis, on the other hand, differs from both roll and yaw in that the magnitudes of control power and damping values enclosed by the pitch boundaries are roughly one-half those of roll and yaw, and the satisfactory region surprisingly tolerates some negative damping.

Some speculation may be offered for these differences in magnitude. The pilots appeared to be more sensitive to pitching accelerations than roll or yaw accelerations. For example, they rarely used control angular accelerations greater than 1 $\text{radian}/\text{sec}^2$ in pitch, whereas roll and yaw accelerations of 3 and 5 $\text{radians}/\text{sec}^2$, respectively, were used frequently, when desirable control characteristics existed.

Combined Two Axes

The results of controlling two axes simultaneously will be discussed for the roll-yaw and pitch-yaw degrees of freedom. Time did not permit study of the pitch-roll combination nor the complete remapping of roll-yaw and pitch-yaw boundaries.

The controllability boundaries that result from the simultaneous control of the roll and yaw axes are presented in figure 6. The dashed lines represent the resulting shifts of the single-axis boundaries when the roll and yaw axes were combined. Only the small portion of the boundaries shown was mapped, and with the controls harmonized. The controls were felt to be harmonized when equivalent control power and damping values for each boundary were combined; for example, a point on the single-axis $3\frac{1}{2}$ roll boundary was combined with the equivalent point on the $3\frac{1}{2}$ yaw boundary, and so on, for other boundaries. For points taken along the line of optimum ratio, figure 7 shows the comparison of pilot rating for combined roll-yaw axes plotted against pilot rating for single-axis control. The 45° line of perfect agreement would result if there were no difference between single-axis and two-axis controllability ratings. For good control systems rated at about 2, the effect of combining axes is small in terms of pilot rating, but increases as the system is deteriorated to a rating of 6 or 7.

However, the resulting shift of boundaries is much larger for the $3\frac{1}{2}$ boundary than for the $6\frac{1}{2}$ boundary. This greater shift is caused by a steeper gradient of pilot rating near the $6\frac{1}{2}$ boundary than near the $3\frac{1}{2}$ boundary. This shifting or shrinking of single-axis boundaries is to be expected, since the additional task of controlling another axis divides the pilot's attention.

The importance of control harmonization became apparent when the control power and damping about one axis were held constant at a satisfactory single-axis value, while the control power and damping about the other axes were varied. For example, roll control power and damping values, located at a point on the single-axis $3\frac{1}{2}$ boundary, were held constant while allowing the yaw control system to deteriorate from a point on the $3\frac{1}{2}$ boundary to one on the $6\frac{1}{2}$ boundary. This caused the roll-control rating to deteriorate from a single-axis $3\frac{1}{2}$ to a combined-axes 6, or a change in rating of $2\frac{1}{2}$, compared with a change of about 1, for harmonized controls. If disharmonious control systems were to be evaluated, there would appear to be a sizable effect on the reshaping of these boundaries. The pitch-yaw combination of axes resulted in shifts of the single-axis boundaries similar to those shown in figure 7 for roll and yaw. These shifts moved the satisfactory boundary for pitch controllability to a point well above the zero-damping level, out of the area of negative damping.

Gyroscopic Coupling

Gyroscopic coupling effects will now be considered for coupling between the pitch and yaw axes. This coupling would result from engines or rotating masses whose spin centerlines are parallel to the longitudinal axis of the airplane. A representative ratio of moment of inertia in pitch to moment of inertia in yaw of 3/4 was assumed, which is an average value for six different VTOL vehicles.

Shown in figure 8 are the pitch-axis and yaw-axis control boundaries with several lettered points along the line of optimum ratio and one point away from the line. These are some of the control power and damping values used in evaluating gyroscopics. Point Ⓐ represents good control characteristics whereas points Ⓑ and Ⓒ represent progressively poor control characteristics. Point Ⓓ is included to illustrate the effects of moving away from the line of optimum ratio.

The effect of gyroscopic coupling on the pilot rating at each of the lettered points is presented in figure 9. The ordinate is the angular momentum of the rotating masses divided by the moment of inertia in pitch, with units of per second (the same as the units for damping). The abscissa is the pilot rating, which represents an "overall" rating since control inputs affect motion of the airplane about both axes. The levels of gyroscopics shown are for several existing VTOL airplanes and one hypothetical airplane, to represent realistic values.

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First, a good control system - point Ⓐ - is considered. The combined-axis rating with no gyroscopic coupling is a satisfactory rating of $2\frac{1}{2}$. The gyroscopic effects became unsatisfactory when a gyroscopic value of about 1 was reached, and unacceptable at about 5. For control systems Ⓑ and Ⓒ, the controllability became unacceptable at somewhat lower gyroscopic values, as would be expected. It should be pointed out here that control systems Ⓑ and Ⓒ characterize a low value of damping and zero damping, respectively. The point away from the line of optimum ratio, shown as Ⓓ in figure 8, appeared to tolerate higher levels of gyroscopic coupling than points Ⓐ, Ⓑ, and Ⓒ, as shown in figure 9. This is surprising, considering that point Ⓓ represents a high sensitivity where one would expect the overcontrolling tendency to aggravate the gyroscopic effects.

A level of gyroscopic coupling is shown in figure 9 that may exist in a hypothetical, 35,000-pound, deflected-jet VTOL vehicle using existing jet engines. If this airplane were provided with control system Ⓐ, an artificial decoupling device must only reduce the gyroscopic couple from a value of 2 to a value of 1 to improve the system to satisfactory. However, if provided with control system Ⓑ, all the gyroscopic moments must be decoupled and further control improvements made before the system will become satisfactory. It appears, therefore, that for a given vehicle with a gyroscopic problem, there is a design compromise of the distribution of available reaction control force between providing good control power and damping, and decoupling the gyroscopic moment with an automatic decoupling device. Of course the most desirable solution to a gyroscopic problem is to eliminate it by designing a vehicle with counterrotating masses that will cancel the precessional gyroscopic moments.

Flight Simulator Comparison

A comparison is made in figure 10 between simulator and flight-determined pilot ratings for the roll degree of freedom. The results for a number of VTOL vehicles are plotted in this figure for comparison with the single-axis boundaries. The actual flight-determined pilot ratings for each vehicle are listed in figure 10 in tabular form. These flight ratings are compared in figure 11 with pilot ratings predicted from the single-axis boundaries, and with the previously shown roll-yaw combined-axis curve. Notice that the pilot ratings obtained in flight are higher in magnitude than those predicted from single-axis results by an amount very similar to the increases which resulted from combining two axes. Similar increases in pilot ratings were noted for the pitch and yaw degrees of freedom when comparing flight results with simulator results. These flight points substantiate the expected shifts of single-axis boundaries when more than one degree of freedom must be controlled. Some preliminary tests have been conducted on the Ames three-degree-of-freedom motion simulator, of simultaneous control of three axes (pitch, roll, and yaw). The resulting control requirements for three degrees of freedom were identical to those obtained for two degrees of freedom. This indicates that little or no change can be anticipated in the two-axis boundaries previously discussed when the additional third degree of angular freedom is added for the special case where controls are harmonized.

Several of the test VTOL vehicles have low values of roll control power making them almost unacceptable in roll. For the yaw degree of freedom, none of the test VTOL vehicles had sufficient control power and damping and all were unacceptable.

Ideal Design

Ideally, the VTOL airplane should be designed to fall well within the satisfactory region of the single-axis boundaries, preferably near the line of optimum ratio. Designing at or near the optimum ratio allows for variations of control power and damping that might result from changes in gross weight of a given airplane. For example, an airplane with a long-range mission could have an appreciable change in gross weight. Assuming that reaction control forces vary with the lifting forces of the airplane or gross weight, and that the moments of inertia vary with gross weight, there could be sufficient changes in maximum control power or damping to make the airplane unacceptable if it were designed right on or near the satisfactory boundary. Designing near the optimum ratio, well into the satisfactory area, also avoids the somewhat "fuzzy" boundary area which has been shown to be variable, depending upon disturbing influences such as combined axes, control harmonization, and so on, not to mention the possible effects of nonlinear control characteristics.

CONCLUSION

It appears that a simulator study of attitude control requirements for hovering has established realistic boundaries for the control about each of the three axes, one at a time, under ideal conditions. Controlling attitude about two axes simultaneously with and without control harmonization, and with the addition of gyroscopic coupling, indicates shifts of the original single-axis boundaries to more restrictive values. Further modification of these boundaries may occur when control of all axes is presented the pilot, with gusts and nonlinearities included. The gyroscopic couple between the pitch and yaw freedom of motion resulted in a rapid deterioration of controllability with increasing amounts of gyroscopic couple, especially when the damping was reduced to low values. A comparison of simulator controllability results with flight indicates good correlation between two-degree-of-freedom simulator results and all-axes results obtained in VTOL airplanes.

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REFERENCES

1. Anderson, Seth B.: An Examination of Handling Qualities Criteria for V/STOL Aircraft. NASA TN D-331, 1960.

2. Tapscott, Robert J.: Criteria for Control and Response Characteristics of Helicopters and VTOL Aircraft in Hovering and Low-Speed Flight. Paper No. 60-51, Inst. Aero. Sci., Jan. 1960.

3. Creer, Brent Y., Stewart, John D., Merrick, Robert B., and Drinkwater, Fred J. III: A Pilot Opinion Study of Lateral Control Requirements for Fighter-Type Aircraft. NASA MEMO 1-29-59A, 1959.

4. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, Mar. 1957, pp. 47-51, 56.

TABLE I.- CONTROL SYSTEM CHARACTERISTICS

1. Linear control gain

2. Constant force gradients
    - (a) Pitch = 3 lb/in. of stick travel
    - (b) Roll = 2 lb/in. of stick travel
    - (c) Yaw = 10 lb/in. of pedal travel

3. Maximum control deflections
    - (a) Pitch = ±6 inches of stick travel
    - (b) Roll = ±5 inches of stick travel
    - (c) Yaw = ±3 inches of pedal travel

4. Effects of nonlinearities neglected
    - (a) Deadbands
    - (b) Friction
    - (c) Hysteresis
    - (d) Time lag

TABLE II.- HOVERING SIMULATION

1. Test conditions
    - (a) Still air: No gust disturbances
    - (b) Out of ground effect: No self-generated disturbances
    - (c) Visual flight conditions
    - (d) No artificial attitude stabilization

2. Scope
    - (a) Single axis: One degree of freedom of motion
    - (b) Combined axes: Two degrees of freedom simultaneously
    - (c) Gyroscopic coupling between pitch and yaw motions

TABLE III.- COOPER PILOT OPINION RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1] Failure of a stability augmenter.

AMES TWO-DEGREE-OF-FREEDOM MOTION SIMULATOR

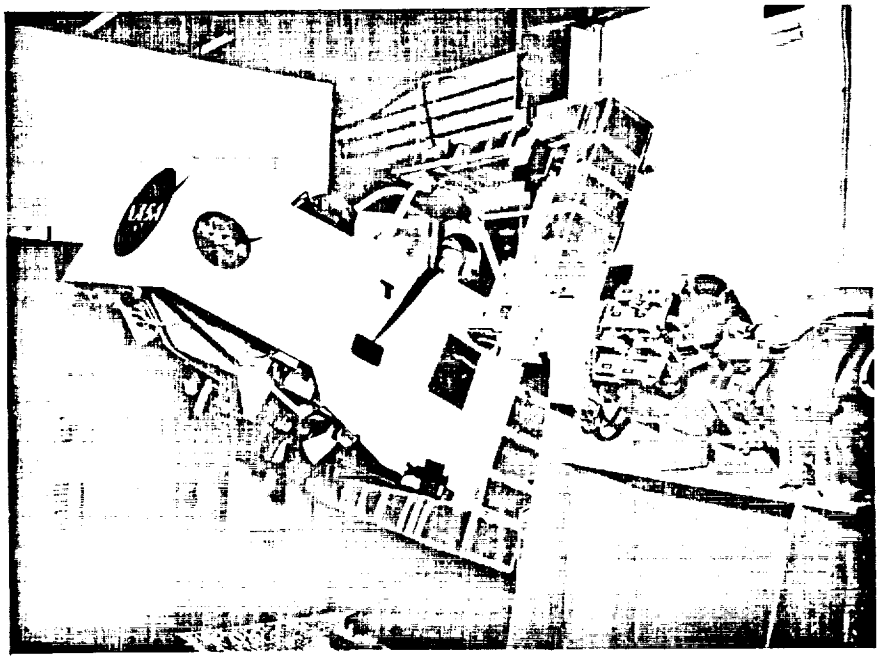


Figure 1

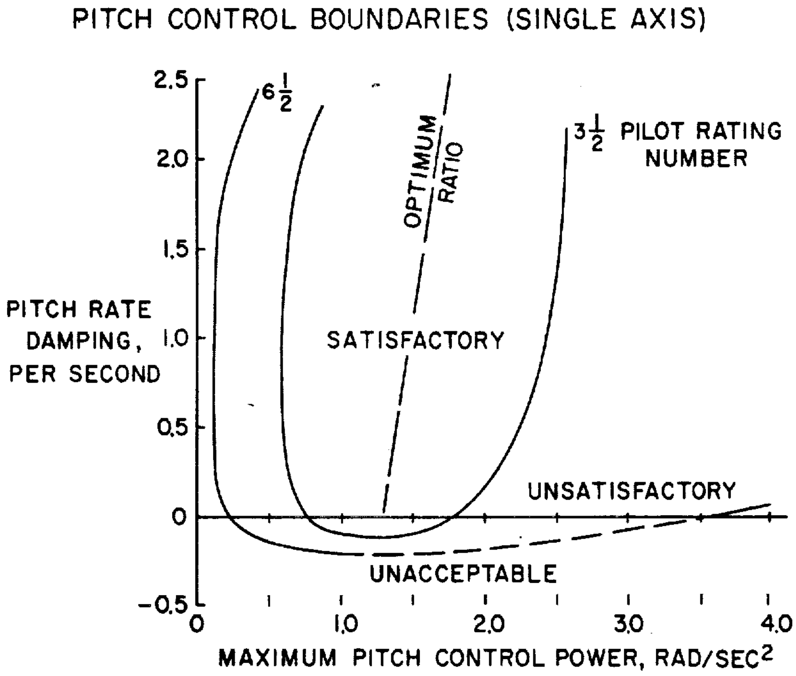


Figure 2

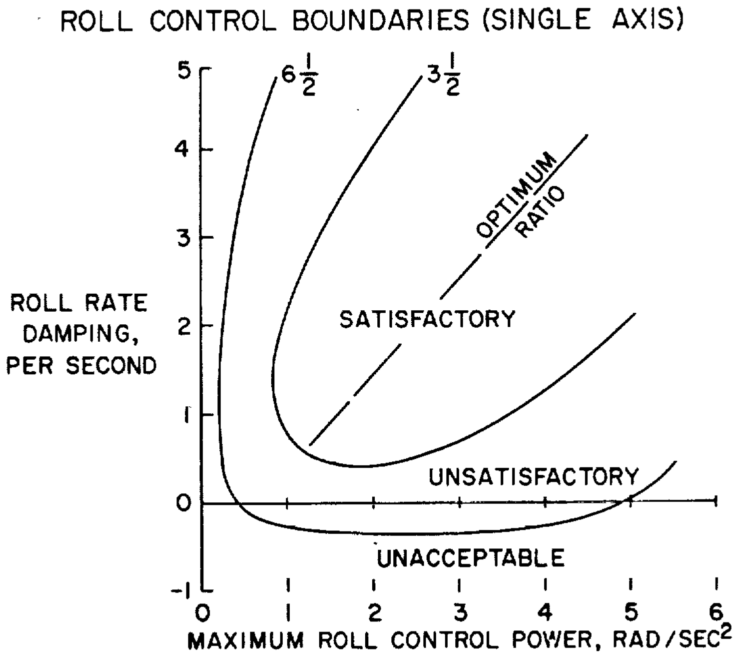


Figure 3

YAW CONTROL BOUNDARIES (SINGLE AXIS)

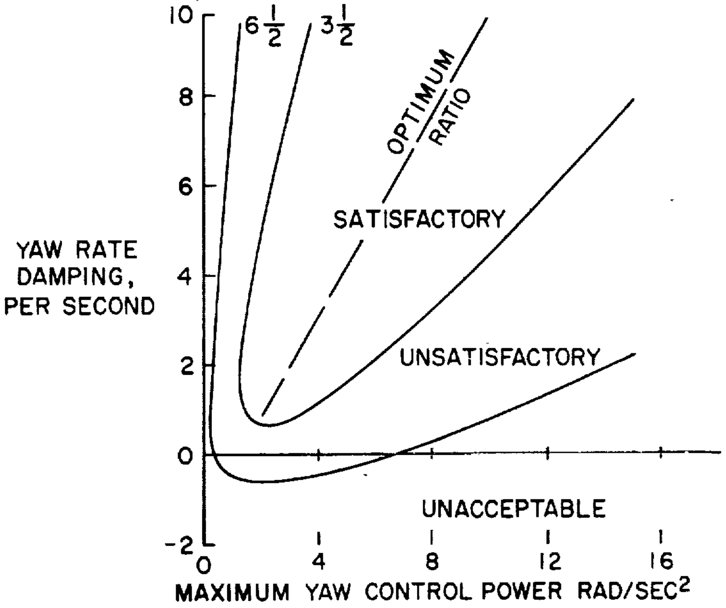


Figure 4

COMPARISON OF PITCH, ROLL AND YAW BOUNDARIES

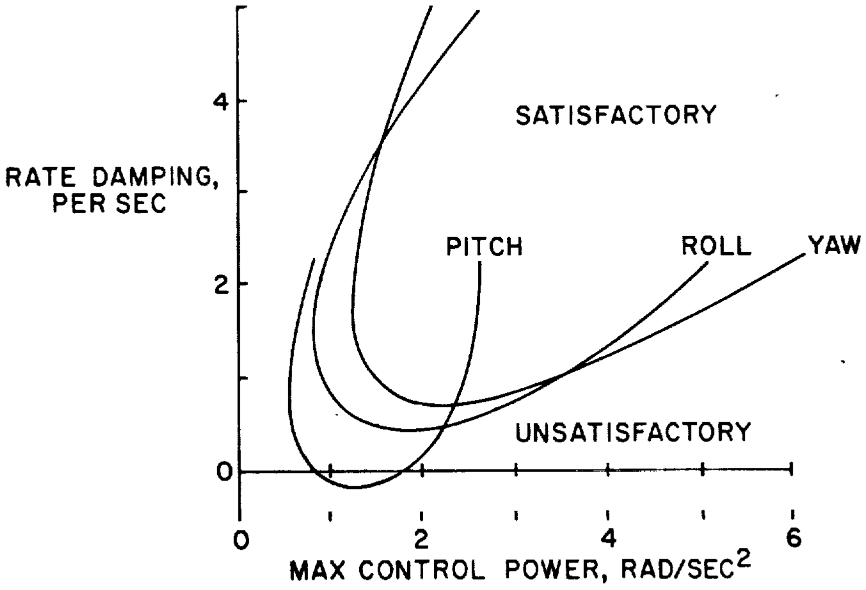
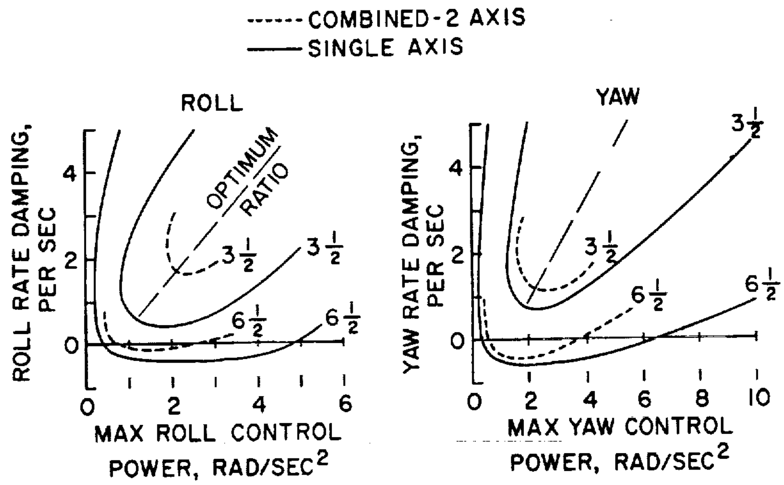
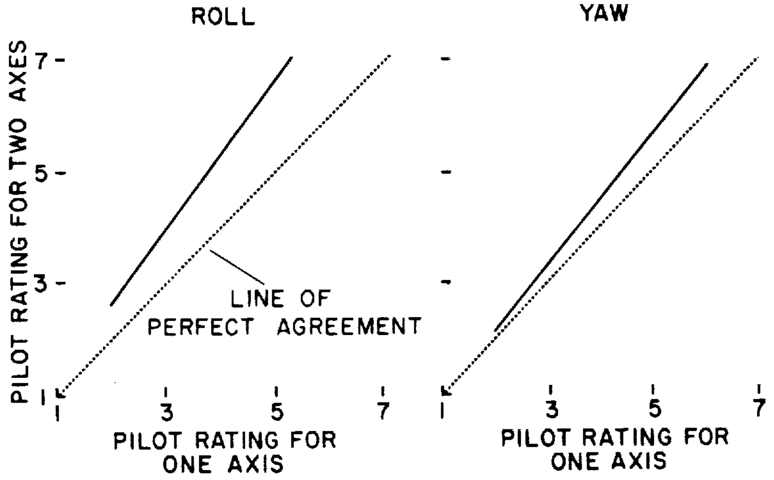


Figure 5



COMBINED ROLL-YAW BOUNDARIES

Figure 6



COMPARISON OF PILOT RATING OF CONTROLLABILITY FOR ONE AND TWO AXES
OPTIMUM RATIO

Figure 7

TEST CONDITIONS FOR GYROSCOPIC COUPLING (SINGLE AXIS BOUNDARIES)

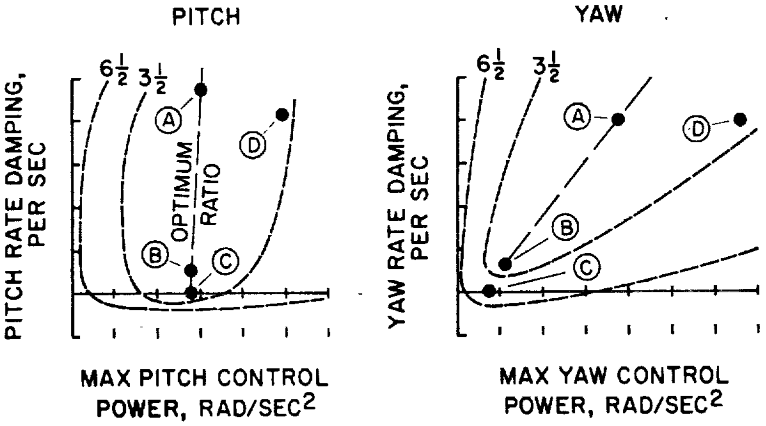


Figure 8

EFFECTS OF PITCH-YAW GYROSCOPIC COUPLING ON PILOT RATING

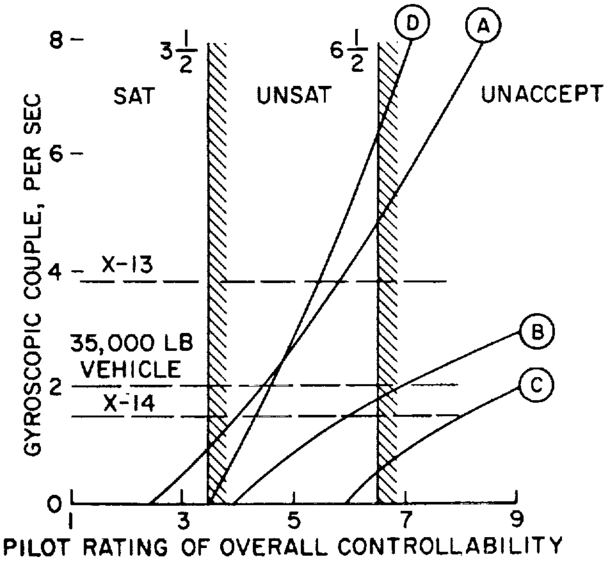


Figure 9

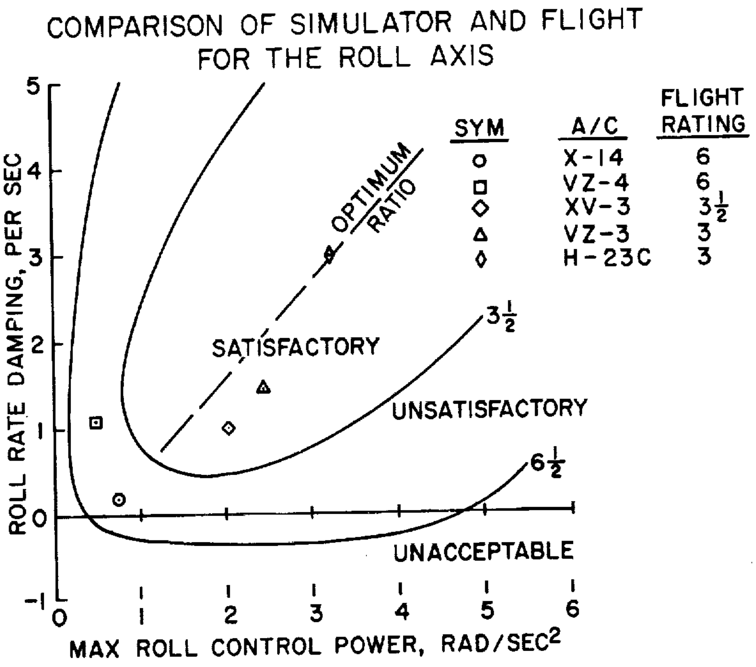


Figure 10

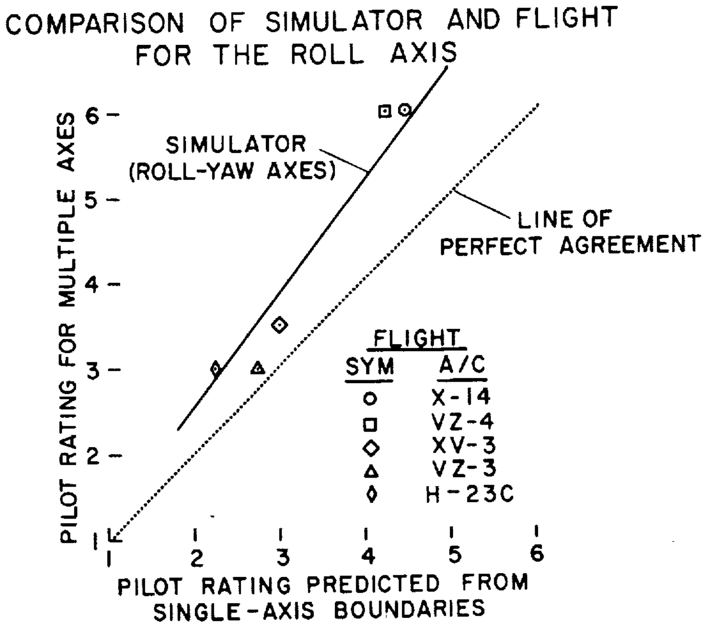


Figure 11