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SUMMARY

A visual flight investigation was conducted with a variable-stability helicopter to contribute toward a basis for establishing VTOL control requirements relative to control power and sensitivity. Control power is defined herein as the maximum angular acceleration which can be produced from a trimmed flight condition, and sensitivity is defined as the angular acceleration per inch of control. In order to permit variations in control power independently of sensitivity, variable-control travel stops were located on the pitch, roll, and yaw controls. A variety of visual tasks was performed including forward, rearward, and sideward flight, quick starts and stops, roll reversals, and hovering turns. The angular velocity damping was held constant at the minimum value required by current specifications throughout most of the investigation. The simulation technique which was employed eliminated trim changes and resisted external angular disturbances.

The results of this investigation indicated that control power was the primary factor which influenced the pilots' ratings of the aircraft's maneuverability whereas sensitivity had only a minor effect. For the performance of precision tasks, neither control power nor sensitivity had an appreciable effect on pilot rating for the range of parameters covered. Comparisons of the minimum satisfactory control power obtained for the maneuver tasks with current VTOL specifications indicated reasonably good agreement (between 3 percent and 20 percent for all axes).

INTRODUCTION

Flight experience with various types of first-generation VTOL aircraft has indicated a characteristic deficiency with respect to both the maximum initial angular acceleration (control power) and the initial angular acceleration per inch of control (sensitivity) in one or more axes. (See refs. 1 and 2.) These deficiencies have been found to create dangerous flight conditions and to impose severe limitations on the aircraft's usefulness at low speed. Because of the absence of a convenient aerodynamic source for producing adequate control moments at low speed, it is common practice to provide the control moments through installation of special moment-producing devices such as fans or bleed air jets. However, such devices absorb energy directly from the installed horsepower and, thereby, significantly reduce the payload. It is therefore of extreme importance that the separate and interrelated effects of the minimum acceptable control power and sensitivity be accurately defined.

Current specifications relating to control power requirements for maneuvering have lacked an adequate basis inasmuch as previous investigations of handling qualities, which contributed greatly toward specifications for sensitivity (for example, ref. 3), were hampered by trim changes caused by static stability and power variations of the available test vehicles. These trim changes tended to mask the maneuvering requirements. It should be noted that trim changes are a function of the specific aircraft configuration or type and, as such, are not a basic ingredient of control power criterion based on maneuver requirements; hence, trim changes must be reckoned with on an individual basis. Only recently have test vehicles and specialized simulation techniques become available which eliminate either the trim changes or their effects and thereby permit a more rigorous study of control power requirements with appropriately designed tasks. One such test vehicle is the X-14A deflected-jet variable-stability VTOL airplane of the 3000-pound weight class, which has been demonstrated to be free of trim changes over the range of flight conditions considered. The X-14A was used to study control power requirements in an investigation reported in reference 4. However, those results were obtained for a constant control travel and as such the related effects of sensitivity on the results were open to question.

Because of the absence of flight research in which the effects of control power and sensitivity had been investigated independently, two concurrent investigations were undertaken. One of these investigations was conducted at the Ames Research Center with the X-14A airplane (ref. 5) and the other, which is reported herein, was conducted at the Langley Research Center with a variable-stability helicopter of the 15 000-pound weight class. The purpose, therefore, of the present investigation was to contribute information toward a basis for establishing the interrelation between control power and sensitivity, and to contribute additional information toward defining the amount of control power required for maneuvering. The model simulation technique, which was employed and which is described in reference 6, eliminated all trim changes and resisted external angular disturbances. Visual flights were conducted for various combinations of control power and sensitivity about the pitch, roll, and yaw axes. A variety of flight maneuvers was performed which were considered representative of those expected of VTOL aircraft.

SYMBOLS

I moment of inertia about principal inertia axis, slug-ft^2

M_Δ moment produced by full-control displacement from trimmed position, lb-ft

M_δ moment per unit control displacement, lb-ft/in.

$M_{\dot{\theta}}$ moment proportional to angular velocity (stable when negative, thus, angular velocity damping), $\frac{\text{lb-ft}}{\text{rad/sec}}$

t_1 maximum time allowed to achieve specified angular displacement, sec

Δ full-control displacement measured from trimmed position, in.

θ_1 angular displacement after time t_1 for full-control displacement, rad

EQUIPMENT AND PROCEDURE

Test Vehicle and Control System

The variable-stability helicopter (a modified YHC-1A) shown in figure 1 was used in the investigation. A detailed description of the variable-stability system and the computer model simulation technique is given in reference 6.

Figure 1.- Variable-stability helicopter. L-63-8407

In order to permit independent variations in sensitivity and control power, variable mechanical stops were located on the controls of the evaluation pilot. Variations in sensitivity were accomplished through electronic gain changes on the signal from the pilot's control stick. The control power available for a given stick travel was therefore established by the simple relation that control power is equal to the sensitivity multiplied by the maximum stick travel from trim (for linear systems). The control trim position was set midway between the control travel limits to provide equal control capability in either direction. Inasmuch as the computer model simulation technique automatically compensated for the test-vehicle trim changes, the trim position of the controls of the evaluation pilot remained fixed throughout the flight. Each of the controls had negligible friction and had a spring gradient of 1 pound per inch in pitch and roll and 5 pounds per inch in yaw.

Test Parameters

Control power and sensitivity.- The combinations of control power and sensitivity which were investigated are indicated in figure 2. For later reference, it should be noted that straight lines drawn through the origin of the plots shown in the figure represent constant values of the control travel limit Δ. In order to maintain reasonable control harmony, variations in the control travel limits (maximum, medium, and minimum) were made for all axes simultaneously.

Angular velocity damping.- Throughout the major portion of the test program, the angular velocity damping was held constant at $-0.5\ \frac{\text{rad/sec}^2}{\text{rad/sec}}$ in pitch, $-1.6\ \frac{\text{rad/sec}^2}{\text{rad/sec}}$ in roll, and $-1.0\ \frac{\text{rad/sec}^2}{\text{rad/sec}}$ in yaw, which is the minimum level specified in references 7 and 8. The importance of providing at least this minimum level of damping had been well documented by previous investigations. Aside from the importance of damping in its own right, these investigations have also indicated that the amount of damping provided has an effect on control-moment requirements. The reason for this dependence may be partially explained by the fact that the steady-state rates which the pilot can develop are defined by the ratio of the control moment to the damping moment (assuming a first-order response). In general, then, an increase in damping above the values used would necessitate an increase in control moment in order to maintain a given degree of angular velocity capability.

Static stability.- For the portion of the program conducted during forward flight, the static directional stability was held constant at 0.3 $\text{rad/sec}^2/\text{rad}$. This value of directional stability was determined as the minimum level for which satisfactory pilot ratings could be obtained during the forward flight phase of the study reported in reference 9. If only the forward flight task were considered, an increase in static directional stability above this value would decrease the yaw control moment requirement. (The static directional stability tends to provide the yawing moment needed to coordinate laterally initiated heading changes.) On the other hand, as is pointed out in reference 9, when the entire flight regime is considered, the yaw control moment

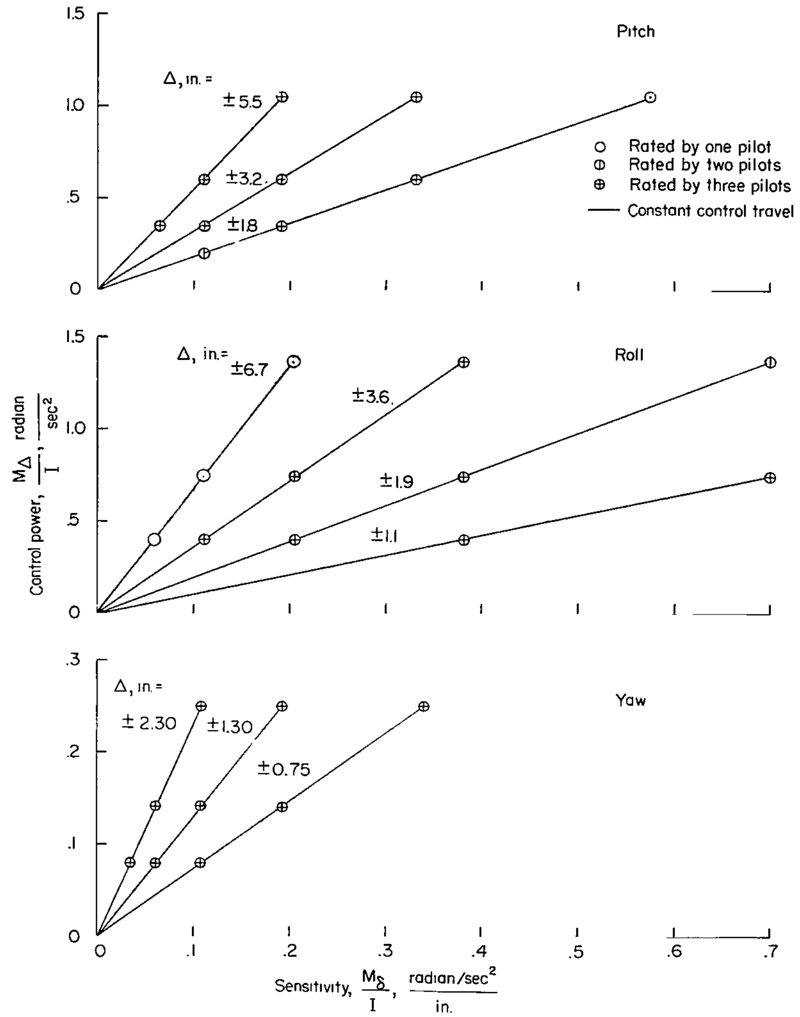

Figure 2.- Combinations of control power and sensitivity evaluated.

requirement does not decrease with increased directional stability (for example, the case requiring decrabbing at touchdown in a cross wind). Therefore, this amount of static directional stability provided a reasonable compromise for the forward flight phase of the program.

During the flight tasks which were performed at or near hovering, the static directional stability was held constant at zero. The static stability derivatives about the pitch and roll axes were held constant at zero throughout the entire program; thus, the primary parameters which permit gusts to produce angular disturbances were eliminated.

Three NASA research test pilots participated in the investigation, two from the Langley Research Center and one from the Ames Research Center. The pilots assigned a numerical rating to the characteristics provided by each test combination for each axis using the rating system presented in table I. The numerical ratings presented in the present paper were obtained by first averaging the evaluation pilots' ratings and then, based on a consideration of the pilots' comments, adjusting the average rating by less than 1/2 rating unit.

TABLE I.- 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[a]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[a]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[a]Failure of a stability augmenter.

DESCRIPTION OF TASKS

Inasmuch as numerous investigations have shown that the results of investigations of handling qualities are directly dependent on the maneuver or task which the pilot is endeavoring to accomplish, each test combination was evaluated for several visual tasks. The tasks used may be logically separated into one of two categories - precision or maneuver - and the results tended to bear out this distinction. A brief description of each task is given in the following sections.

Maneuvering Tasks

Hovering turns.- The hovering turns, which consisted generally of 360° turns, were judged both on the basis of the maximum yaw rates which could be developed and on the ease with which turns could be initiated and terminated on the selected heading. In some cases, where only very small yaw rates were obtainable, heading changes of 90° were used to conserve flight time.

Roll reversals.- The roll reversals were initiated from a hover by rolling the aircraft to establish a bank angle (hence, a linear acceleration) from which a rapid roll was made in the opposite direction in order to stop at a predetermined spot, which was followed by leveling up so as to remain over the spot. This maneuver permitted the pilot to assess the aircraft's limitations in lateral maneuver capability.

Turn reversals at low forward speed.- The pilot made visual descending approaches on the runway heading with an intentional misalinement of about 300 feet at speeds as low as 35 knots. At a distance of about 300 feet from the runway threshold the pilot commenced a rapid S-turn maneuver so as to aline the aircraft with the runway center line.

Quick starts and stops.- During the quick starts and stops, the helicopter was pitched down to obtain a rapid linear acceleration until an airspeed of about 45 knots was attained. At this point, the pilot rapidly pulled up the nose and decelerated to a hover.

Precision Tasks

Precision hovering.- The precision hovering task involved attempts at proceeding to a point directly over a spot on the ground, stopping, and accurately maintaining this position. This task was performed at heights not greater than 20 feet so as to provide a close visual reference.

Square hovering pattern.- This task was performed at a height of less than 20 feet and consisted of forward, sideward, and rearward flight to specific points at a constant heading. The pattern, approximately 150 feet square, was performed at a rate such that the maneuver required about 90 seconds.

RESULTS AND DISCUSSION

Maneuver Task Results

Pitch axis.- The results obtained during the maneuver tasks for the pitch control are presented in figure 3. These ratings were obtained during the quick start and stop maneuver which provided the most critical task for the longitudinal control. An average deviation of slightly less than 0.5 pilot-rating units existed for these ratings. A $3\frac{1}{2}$ boundary (boundary between satisfactory and unsatisfactory) is plotted in the figure. This boundary indicates that the minimum satisfactory longitudinal control power was about 0.47 rad/sec^2. On the basis of the combinations investigated, it was not possible to predict the location of a $6\frac{1}{2}$ boundary (boundary between unsatisfactory and unacceptable). Therefore, a relatively small amount of longitudinal control power did not appear to severely restrict the maneuvering capability in pitch. In practice, however, trim needs and instabilities have often left the amounts of control power provided highly inadequate.

Although the data points of figure 3 fairly well defined the lower portion of the $3\frac{1}{2}$ boundary (or the minimum control power required), it was not feasible to investigate sensitivities which were sufficiently low to define the minimum sensitivity with any degree of certainty. The reason that lower sensitivities could not be investigated may be seen from figure 2, which illustrates that the maximum control travel-limits dictate the minimum value of sensitivity which can be investigated for a given value of control power. Therefore, in order to permit extrapolation of the $3\frac{1}{2}$ boundary into the untested region a separate requirement based on maximum control travel was considered. The maximum control travel as specified in HIAD (Handbook of Instructions for Aircraft Designers, ref. 10) is ±7 inches for the pitch axis and corresponds to the maximum throw which can be used effectively from a physical standpoint. Thus, if the range of sensitivites had been reduced much further, the ratings would probably deteriorate, if for no other reason, because of the large control travel necessary to achieve the required control power. Figure 3 shows that with the exception of the highest sensitivity point, there was essentially no change in pilot rating with changes in sensitivity.

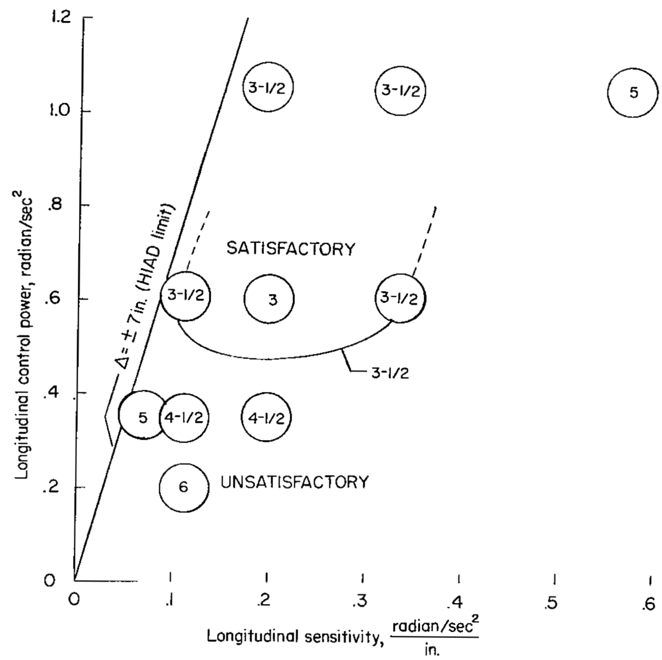

Figure 3.- Pitch results for maneuver task.

<u>Roll axis</u>.- Turn reversals at low forward speed and roll reversals in hovering provided the most demanding tasks for the roll control, and the results are presented in figure 4. The average deviation for these points was

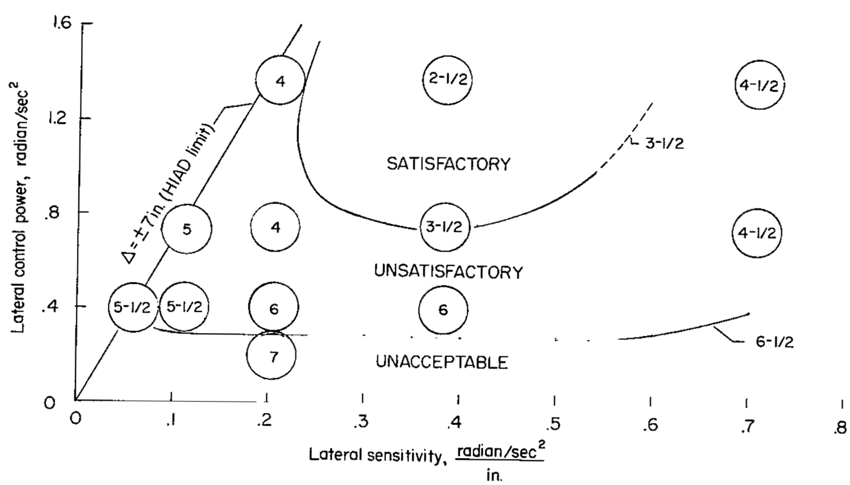

Figure 4.- Roll results for maneuver task.

0.6 pilot-rating unit. The control power results for the roll axis indicated that the lower limit on satisfactory control power was about 0.75 rad/sec^2. For control powers on the order of 0.4 rad/sec^2, the pilots consistently used full control in executing both the roll reversals and the turn reversals during the landing approach, and one pilot commented that for this low value of control power, he was forced to "plan ahead" very carefully for this maneuver so as to terminate the maneuver at a predetermined spot. For these reasons the pilot ratings for this level of control power approached unacceptable, and for the one value of control power below 0.4 rad/sec^2, the rating fell well within the unacceptable region.

Figure 4 shows that the HIAD control travel-limit correlates well with the portion of the $3\frac{1}{2}$ boundary which is related to a lower limit on satisfactory sensitivities. Figure 4 also shows that the effects of sensitivity become appreciable only when the control power reaches a satisfactory level.

<u>Yaw axis</u>.- Turn reversals during landing approaches and the yaw turns during hovering appeared to provide equally demanding tasks for the yaw control, and the ratings are shown in figure 5. The average deviation was 0.25 pilot-rating unit. Again, the HIAD maximum allowable control travel which is specified at ±3.25 inches for the yaw axis was used in extrapolating a portion of the $3\frac{1}{2}$ boundary in figure 5. Because of insufficient control power, none of the test combinations were rated satisfactory - even at the maximum value which could be simulated. In order to permit comparisons with current specifications in a following section, it was necessary to determine the approximate location of the minimum control power boundary. The minimum acceptable control power as indicated by the $3\frac{1}{2}$ boundary in figure 5 was extrapolated from the available data in the following manner: Since the effects of sensitivity were small, a single representative rating for each level of control power was obtained by averaging all the ratings for a given control power. These resulting variations in pilot rating with control power are shown in figure 6. This figure indicates that a $3\frac{1}{2}$ rating would probably be obtained at a control power of approximately 0.4 rad/sec^2, which is indicated in figure 5 by the dashed-line boundary. Since the maximum control power which could be achieved was so much less than what would be considered satisfactory, the pilots indicated that they were not concerned with sensitivity.

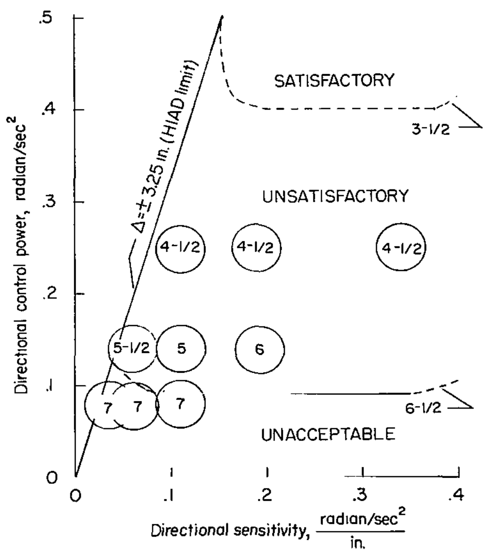

Figure 5.- Yaw results for maneuver task.

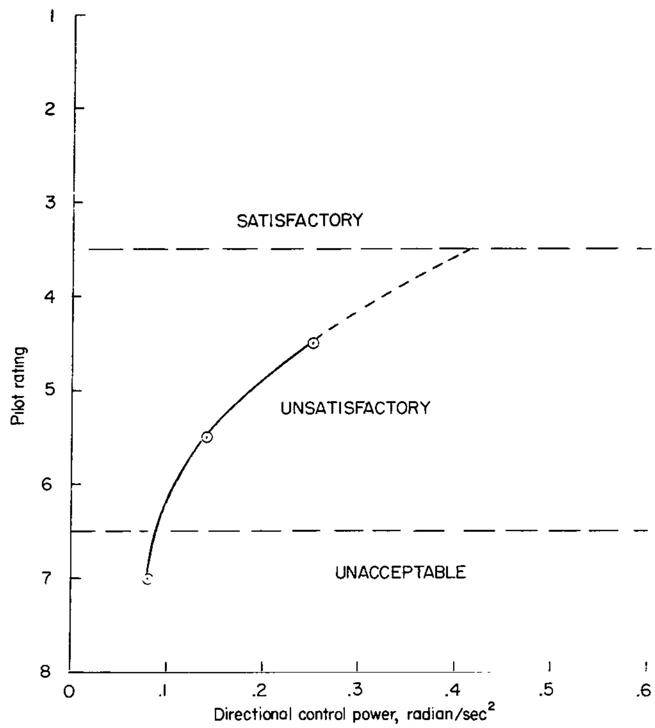

Figure 6.- Variation of pilot rating with yaw control power.

Precision Task Results

The results obtained during precision tasks for the pitch, roll, and yaw control are presented in figure 7. The ratings presented in the figure represent an average of the ratings assigned by the three pilots. These results indicate very little variation in pilot rating with changes in control power or sensitivity. It appears, therefore, that for the range of parameters covered, these precision tasks did not put a high premium on either control power or sensitivity. Possible reasons for the lack of appreciation for these parameters (a result which appears to conflict with VTOL test-bed experience) are thought to be (1) The control system characteristics, which, being relatively free of friction permitted precise positioning of the controls and positive control centering. (2) The simulated zero static stability prevented gusts from producing angular upsets. (3) The level of damping, which was simulated, provided more nearly a desirable angular velocity control rather than an acceleration control. Also, the simulation technique which was employed resisted external angular disturbances acting on the test helicopter. These results, nonetheless, imply by comparison with the maneuver results of the previous section and the instrument results of reference 3 that control power and sensitivity should not be judged satisfactory solely on the basis of visual hovering tasks, but rather on the entire spectrum of flight operations intended.

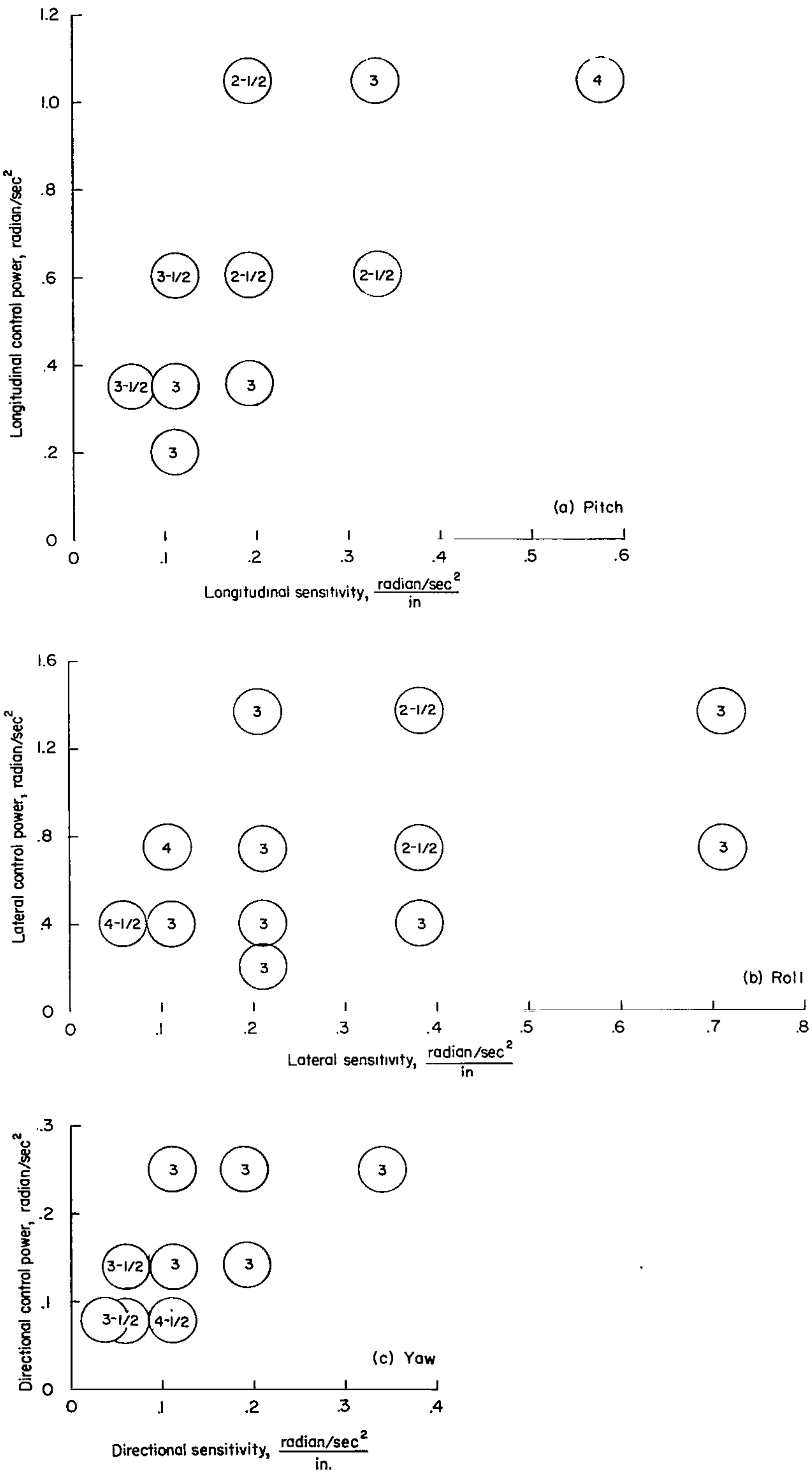

Figure 7.- Precision task results.

Effect of Reducing Damping

In order to provide some insight as to the extent to which the angular velocity damping influenced the pilot ratings, one flight was made with the damping in all axes reduced to one-fourth of the AGARD requirements (ref. 7). During this flight, the control power was held constant at 0.6, 0.74, and 0.14 rad/sec^2 for the pitch, roll, and yaw axes, respectively. For these conditions, the control characteristics deteriorated for the most critical tasks by slightly more than one-half unit on the pilot-rating scale. This result indicates that reduction in the damping below the AGARD requirement does not permit reduction in the control moment requirements, even though the lower damping permits greater angular displacement during a given time interval.

Comparison of Maneuver Control Power Results With Current Handling Qualities Specifications

Current control power requirements are specified in the literature (refs. 7 and 8) in terms of a minimum angular displacement which should be produced after a given time by the maximum control travel from the trimmed position. In order to permit comparison between the present control power results and current requirements, the following procedure was used to derive control power values from the displacement criteria. By assuming that the aircraft response is described by a first-order system (a system containing only a mass and a damper), the following equation for the control power M_Δ/I required to produce a given displacement θ_1 after a time t_1 was derived:

$$\frac{M_\Delta}{I} = \theta_1\left[\frac{\left(\frac{M_{\dot\theta}}{I}\right)^2}{-\frac{M_{\dot\theta}}{I}t_1 + e^{\frac{M_{\dot\theta}}{I}t_1} - 1}\right]$$

where $M_{\dot\theta}/I$ is the ratio of the angular velocity damping to the inertia. By using the values of θ_1 and t_1 specified in references 7 and 8 and the value of $M_{\dot\theta}/I$ used during the testing, minimum specified values of control power were computed for the 15 000-pound helicopter used in the present investigation and for the 3000-pound airplane used in reference 4. These values are presented in table II.

The minimum satisfactory control power values obtained with the YHC-1A helicopter during the present investigation and those obtained with the X-14A VTOL airplane during the study reported in reference 4 are compared in figure 8 with their respective requirements, which are given in table II. The comparison shown in figure 8 is presented as the ratio of the minimum satisfactory control power obtained to the control power required by the specifications of references 7 and 8. Hence, the ratio of 1.0 would indicate exact agreement.

TABLE II.- TABULATION OF VALUES USED IN COMPUTATION OF CONTROL POWER REQUIRED BY CURRENT SPECIFICATIONS

Source	Axis	Minimum value of θ_1 required by specifications, rad		Maximum time t_1 allowed to achieve θ_1, sec	Value of $M_{\dot{\theta}}/I$ used in tests, 1/sec		Computed value of M_{Δ}/I based on specification requirements, rad/sec^2	
		YHC-1A	X-14A		YHC-1A	X-14A	YHC-1A	X-14A
Reference 7 (AGARD)	Pitch	0.21	0.32	1.0	-0.5	-0.8	0.49	0.84
	Roll	.21	.32	1.0	-1.6	-3.0	.67	1.4
	Yaw	.12	.19	1.0	-1.0	-1.0	.33	.53
Reference 8 (MIL-H-8501A; contact)	Pitch	0.13	0.19	1.0	-0.5	-0.8	0.30	0.5
	Roll	.056	.09	.5	-1.6	-2.2	.58	.98
	Yaw	.23	.36	1.0	-1.0	-1.0	.61	.97
Reference 8 (MIL-H-8501A; instrument)	Pitch	0.20	0.32	1.0	-0.5	-0.8	0.48	0.81
	Roll	.07	.10	.5	-1.6	-3.0	.69	1.3
	Yaw	.23	.36	1.0	-1.0	-1.0	.61	.97

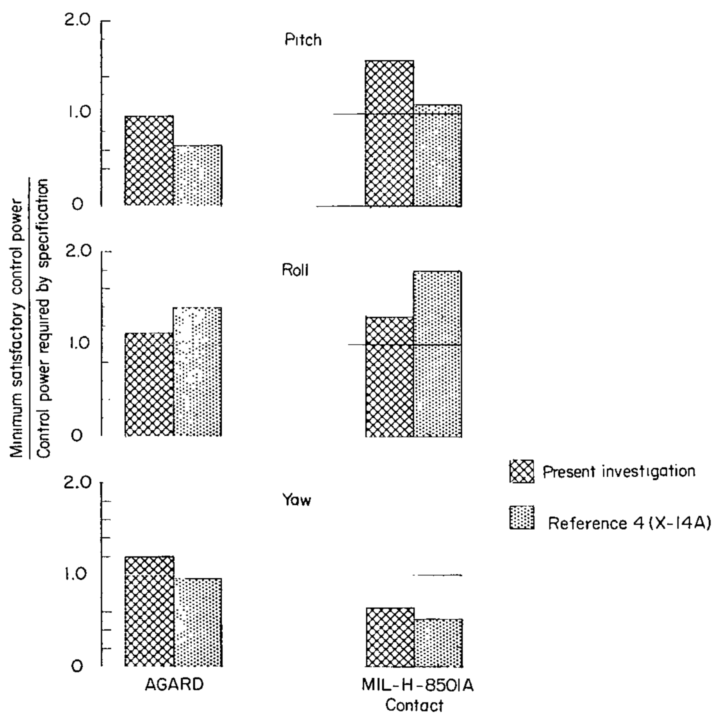

Figure 8.- Comparison of control power results with current requirements. (Yaw value of present investigation based on extrapolated $3\frac{1}{2}$ boundary in fig. 5.)

Figure 8 shows that the pitch, roll, and yaw results of the present investigation are in reasonably good agreement with AGARD specifications. Specifically, these results are 3 percent lower for pitch and 15 percent and 20 percent higher for roll and yaw, respectively, than the specifications. Therefore, for the scope of this investigation the AGARD specification seems to provide adequate criteria for the 15 000-pound class of VTOL aircraft for maneuvering. The comparison of the results from reference 4 with the AGARD specifications for the 3000-pound X-14A airplane indicates very close agreement only in the case of the yaw axis.

The comparison in figure 8 of the present results with the contact-flight specifications of reference 8 (MIL-H-8501A) indicates that the correlation for each axis was not as close as that obtained for the corresponding AGARD comparisons. As a matter of interest, comparisons of the present results with the instrument specifications of MIL-H-8501A, listed in table II, indicate as good agreement for the pitch and roll axes as the corresponding AGARD comparisons previously discussed. The fact that better agreement was obtained with the instrument specifications than with the contact-flight specifications is not surprising when the broad intent of the specifications is considered. In addition to encompassing the minimum requirements for satisfactory instrument operation, the instrument-flight specifications were intended to provide a more stringent set of specifications for general applicability, whereas the contact-flight specifications were intended for application under less exacting circumstances.

With regard to the comparisons for yaw control power shown in figure 8 which indicate poorer agreement with the MIL-H-8501A specifications than with the AGARD specifications, it is of interest to note that the earlier version of MIL-H-8501A, designated MIL-H-8501, had called for considerably less control power which would have shown closer agreement with the current results. The revision of the earlier specification to the present one is understood to have been based on practical experience together with research results, which, because of trim changes and high static stability of the test vehicle used, were difficult to apply to the development of maneuver criteria. The directional control power results of the present investigation indicate, therefore, that the revision to the earlier specification was in the proper direction although it may have been too large.

CONCLUSIONS

A visual flight investigation was conducted with a variable-stability helicopter to contribute toward a basis for establishing the interrelation between control power and sensitivity and to contribute additional information toward defining the amount of control power required for maneuvering. Trim changes of the test vehicle were eliminated and angular upsets due to external disturbances were resisted by the model simulation technique which was employed. The model simulated the minimum angular velocity damping required by current specifications and zero static stability with the exception of the forward-flight work where a stable level of static directional stability was used. On the basis of this investigation, the following conclusions are drawn:

1. Variations in control power had a predominant effect on pilot appreciation of aircraft maneuverability whereas variations in sensitivity over a relatively wide range had only a negligible effect on the performance of the visual-maneuvering tasks. (These sensitivity results should not be applied indiscriminately to varied situations, particularly visual flight in extreme turbulence and instrument flight, both of which impose more severe requirements on sensitivity.)

2. Under conditions of precision hovering wide variations in either control power or sensitivity had no appreciable effect on aircraft handling characteristics.

3. Reduction in the angular velocity damping to one-fourth the minimum value required by current specifications, while control power and sensitivity remained constant, resulted in poorer pilot ratings even though the reduction permitted a greater angular displacement during a given time interval.

4. The minimum levels of control power which were required to provide satisfactory maneuver capability were compared with current specifications. The comparisons showed reasonably good agreement for the pitch, roll, and yaw axes (between 3 percent and 20 percent).

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 21, 1965.

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