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CRITERIA FOR PRIMARY HANDLING QUALITIES CHARACTERISTICS OF VTOL AIRCRAFT IN HOVERING AND LOW-SPEED FLIGHT

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INTRODUCTION

In establishing criteria for hovering and low-speed characteristics for the newer types of VTOL aircraft, one approach has been to draw upon helicopter criteria in this region. In certain cases, this approach would require some extension of the ranges of operating and design conditions for which the helicopter criteria were established. In other cases, the newer VTOL configurations have characteristics which are already within the ranges for which the earlier criteria have been established in helicopter studies. It is believed that this discussion will, to some extent, indicate the applicability of these criteria to the newer VTOL configurations. In addition, the experience obtained with the present generation of VTOL research aircraft will be drawn upon and criteria for several fundamental characteristics will be suggested.

SYMBOLS

t	a given time
I, I_X, I_Y, I_Z	moments of inertia
W	weight of airplane
A, B	constants representing coefficients of control power and damping expressions, respectively (table I)

AIRCRAFT CHARACTERISTICS DURING HOVERING AND LOW-SPEED FLIGHT

Initial Response to Controls

Probably the most significant of recent handling qualities criteria for low-speed and hovering flight relate to initial response to control

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characteristics. Figure 1 illustrates such a response and the particular characteristics which are important. The control input is shown, for illustrative purposes, as a step input; the lower curve illustrates a typical buildup of the angular velocity of the aircraft in response to the control input. The first parameter of importance is characterized by the initial slope of the angular velocity curve. The second parameter is characterized by the time taken for the angular velocity to reach a given percentage of the resulting steady-state value. The response characteristics are determined, respectively, by the control power, or moment per unit control deflection tending to produce angular acceleration, and the angular-velocity damping, or moment proportional to and opposing the angular velocity, as illustrated by the diagrams at the top of figure 1.

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In order to establish a criterion for these parameters, use has been made of pilots' comments and flight measurements for a range of aircraft sizes; however, the main basis has been the studies with the variable-response helicopter, in which these parameters could be adjusted over a range for trial in flight. Both statistical analysis of flight records and pilots' comments were used to get boundaries of the type shown in figure 2. Boundaries such as these, showing the degree of acceptability of various combinations of control power and damping, were determined for each aircraft control axis. The rather extensive data from which these boundaries were determined are published in reference 1 and will not be repeated herein. Most of this experience has been with lower than acceptable values, with at least one aircraft experiencing higher than acceptable values of roll control power.

These boundary-plot results were combined with other data for gross weights from 1,000 to 10,000 pounds and with more limited data and experience at a gross weight of 30,000 pounds. From this information a criterion for each axis was derived as a function of size; these criteria are shown in equation form in table I. These formulas give values of control power in terms of the number of degrees of angular displacement of the aircraft in a given time following a control input and angular-velocity damping in terms of $\frac{\text{ft-lb of moment}}{\text{radians/sec}}$. Each formula has two constants, one to represent minimum characteristics for visual flight and another of higher value to represent the more stringent needs of instrument flight.

To satisfy control needs for the precision maneuvers or tasks, the total control - that is, inches of travel with the per inch values of control power specified for the respective axes by the formulas - should be at least ±4 inches longitudinally, ±3 inches laterally, and ±3 inches for the pedals. It should be noted that these amounts of total travel are the minimum necessary to satisfy precision maneuvering needs and any requirements for more gross maneuvering or for use of the primary controls for trim purposes during steady flight should be added to these values.

Variation of Response Parameters With Aircraft Size

With respect to the variation in response with size, permitted by the formulas given in table I, figure 3 shows, in general form, the variation of control power and damping, when the formulas are applied to a family of aircraft over a range of gross weights. The reduction, shown in figure 3, for control power and damping parameter as aircraft size increases is in keeping with previous airplane criteria. It has been suggested that constant angular acceleration be required over the size range to provide sufficient maneuverability of the larger aircraft; in this respect it should be noted that the reduction indicated for these parameters represents essentially constant angular-velocity capabilities over the entire size range.

In order to provide a somewhat more direct insight into what the reduction represents, the case of yaw has been considered where an angular acceleration produces a side force at points on the aircraft other than at the center of gravity. Figure 4 illustrates the variation with size of the side force at a given location - in this case, the front of the fuselage where the pilot is generally located. The solid curve shows that when the yaw criterion is applied, the side force due to yaw, for typical full pedal movement of 3 inches, would be essentially constant at about $\frac{1}{4}$ g regardless of the size of the aircraft. For comparison, the dashed curve shows that, when the higher values of control power, such as have been found desirable for aircraft at a gross weight of 5,000 pounds, are maintained as the aircraft size goes up, a side force on the order of 1 g would result for full pedal deflections for even moderately larger sizes. From this it would appear that providing constant angular acceleration over the entire size range might result in characteristics that might be undesirable as well as very expensive, designwise, to get.

The exact form of the criteria formulas, however, needs more substantiation, particularly at the larger sizes.

Transition Characteristics

There are a few parameters for control during transition which appear likely to need specific attention in order to fill in the gaps in the previous criteria and to insure acceptable characteristics in this flight range. Table II presents three of these items.

Trim changes.- The first factor for trim changes has to do with the margin of control remaining between the amount used for trim and the amount available, to allow for disturbances and for maneuvering the aircraft with some decisiveness. In this respect it is recommended that a margin of at least 20 percent of the available control be demonstrated during transitions with a rate of acceleration or deceleration of $\frac{1}{4}g$ - that is, a rate of change of forward speed of at least $\frac{1}{4}g$.

The second factor relates to the rate at which any permissible trim changes occur. If changes in trim occur so abruptly that the pilot cannot react fast enough to keep the aircraft from being out of trim over a short period of time, then even relatively small trim changes can become sources of considerable disturbance to the aircraft. Since the problem in this respect is one of reaction time or, in the case of instrument flying, of scanning plus reaction time, a proposed criterion would appear best related to the shortest period of time over which the required change in control position would have to be made. Thus the recommendation is that during the transition, again with at least a rate of change of forward speed of $\frac{1}{4}g$, rates of stick movement to maintain trim be no greater than 1 inch per second. Expressed another way, this represents about a 1-inch change in trim stick position for any 5-knot change in airspeed during the conversion or transition with a rate of change of $\frac{1}{4}g$.

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Speed stability.- It appears desirable to place a limit on the maximum amount of speed stability. In the hovering and low speed range, the speed stability has direct bearing on the magnitude of the aircraft disturbance caused by horizontal gusts; it affects the oscillatory period and to some extent determines the usable speed range for fixed configuration of the lifting elements. In terms of the potential disturbance caused by inadvertent speed changes, it would appear desirable for a 10-knot gust, for example, to cause no greater disturbance than would a 1-inch control input. The tentative criterion, then, is to limit the maximum speed stability to that which would be represented by a slope of $\frac{1}{10}$ inch per knot on the curve of control position plotted against speed. Some experience with a VTOL aircraft with about this amount of speed stability at very low speeds has shown this to be about the limit for acceptable handling qualities.

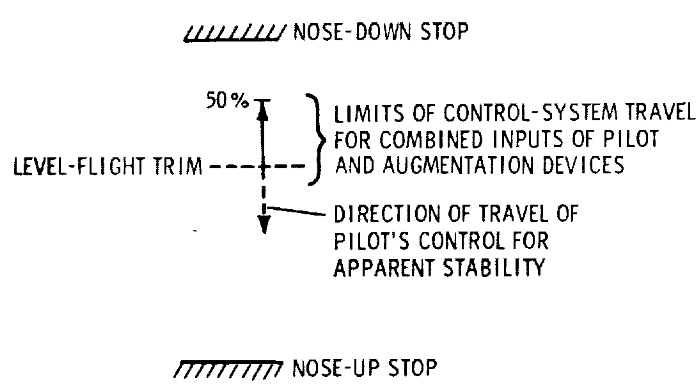
Limitation on number of pilot-operated controls.- The next characteristic, that of the total number of pilot-operated controls, while not the most fundamental, appears to warrant some restrictions to avoid saturation of the pilot. In this respect five controls seem to be about the maximum tolerable. Counting the lateral, longitudinal, and directional controls and adding the power control, there are four controls for most VTOL aircraft. The addition of the control for the lifting-element angle or configuration change brings the total up to the limit of five. It is of importance here to note that these five controls should be arranged in a manner such that the pilot is not required to release any control to manipulate another.

CRITERIA FOR USE OF STABILITY AUGMENTATION DEVICES

The characteristics which are judged necessary to insure adequate handling qualities have been discussed without regard to the mechanism by which these characteristics are obtained. In many cases the characteristics of VTOL aircraft, as well as of helicopters, invite the use of devices to provide some measure of the flying qualities parameters which are desired. As the reliability of available electronic components improves, such a procedure may become even more attractive. The basic problem exists, even for perfectly reliable devices, of insuring adequate control moment capability for the pilot and the devices. In particular, for those cases where automatic inputs into the primary control mechanisms must overcome unstable moments as well as generate the moments needed to provide the desired stability, some limitations must be observed to avoid catastrophic conditions. Table III shows the form of the criteria for the two most likely sources of difficulty when augmentation systems are used. The first is the situation where the basic airframe has static instabilities which must be overcome, and, second, the case where unstable damping moments must be overcome.

Static Instabilities

In order to insure some margin of control-system travel during maneuvering flight, it is recommended that, during specific test maneuvers, each of which would be selected to bring out the static characteristics, the combined inputs of the pilot and augmentation systems should utilize no more than 50 percent of the control moment remaining between the level flight trim position and the stops. The following sketch illustrates both the potential problem and the criterion by showing the control-system travel involved:



Consider the longitudinal axis where angle-of-attack instability would be the problem. The movement of the longitudinal control during a steady level turn is in the aft direction for apparent angle-of-attack stability. For the case where the apparent stability is provided by augmentation through the primary controls, the control system, after initially moving in the aft direction to initiate the maneuver, would move back past the trim position. The criterion, then, is that no more than 50 percent of the available travel should be used to provide the desired apparent stability and thus, in effect, limits the magnitude of the unstable moments of the airframe in relation to the available control moments. For the helicopter, a level-flight turn to design load factor at cruise speed is the designated critical maneuver for the longitudinal axis. For other VTOL configurations, flight conditions within the low-speed and transition region are likely to be more critical with respect to relative magnitudes of the available control moments and unstable airframe moments.

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The criterion for control-system travel applies also to the roll and yaw axes with maneuvers involving sideslip to demonstrate the amount of control-system motion required to provide the apparent directional stability and the desired degree of dihedral effect or roll moment due to sideslip.

Unstable Damping

For the case where an augmentation system using the primary control mechanism must overcome unstable damping moments as well as provide the desired amount of stable damping moments, a similar control problem could result; a 50-percent rule similar to that discussed for the unstable static moments can be applied also by limiting the absolute value of any unstable damping moments of the airframe to 50 percent of the absolute value of the resulting stable moment.

CONCLUDING REMARKS

Although there are many gaps in the criteria presented, some of the major points with respect to characteristics at low speeds and the potential problem areas have been discussed. Criteria have been shown for the initial response characteristics, for some fundamental control characteristics in transitions, and for the use of devices to provide these characteristics. Although a lot remains to be done in this respect, it is believed that adherence to these minimum criteria will result in a good start toward obtaining vehicles with reasonable flying qualities.

REFERENCE

1. Salmirs, Seymour, and Tapscott, Robert J.: The Effects of Various Combinations of Damping and Control Power on Helicopter Handling Qualities During Both Instrument and Visual Flight. NASA TN D-58, 1959.

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TABLE I

CRITERIA FOR MINIMUM ACCEPTABLE CONTROL POWER AND ANGULAR-VELOCITY DAMPING

AXIS	ANGULAR-VELOCITY DAMPING, $\frac{\text{FT-LB}}{\text{RADIAN/SEC}}$	ANGULAR DISPLACEMENT IN GIVEN TIME FOR 1-INCH CONTROL DISPLACEMENT, DEG
VISUAL		
PITCH	$8(I_Y)^{0.7}$	$45/\sqrt[3]{W+1000}$ (1 SEC)
ROLL	$12(I_X)^{0.7}$	$27/\sqrt[3]{W+1000}$ $\left(\frac{1}{2}\text{ SEC}\right)$
YAW	$27(I_Z)^{0.7}$	$110/\sqrt[3]{W+1000}$ (1 SEC)
INSTRUMENT		
PITCH	$15(I_Y)^{0.7}$	$73/\sqrt[3]{W+1000}$ (1SEC)
ROLL	$25(I_X)^{0.7}$	$32/\sqrt[3]{W+1000}$ $\left(\frac{1}{2}\text{ SEC}\right)$
YAW	$27(I_Z)^{0.7}$	$110/\sqrt[3]{W+1000}$ (1SEC)

TABLE II

CONTROL CHARACTERISTICS IN TRANSITION

CHARACTERISTIC	RECOMMENDED CRITERIA
TRIM CHANGES	
A. MARGIN	AT LEAST 20% OF AVAILABLE CONTROL MOMENT SHOULD REMAIN AT A $\frac{1}{4}$g RATE OF ACCELERATION OR DECELERATION
B. RATE	TRIM CHANGE SHOULD NOT REQUIRE CONTROL MOVEMENTS AT A RATE GREATER THAN 1 INCH PER SECOND AT $\frac{1}{4}$g RATE OF ACCELERATION OR DECELERATION
SPEED STABILITY	AT ALL TRIM CONDITIONS, SHOULD BE LIMITED TO A MAXIMUM STICK DEFLECTION OF 0.10 IN./KNOT
NUMBER OF PILOT-OPERATED CONTROLS	SHOULD NOT EXCEED FIVE

TABLE III

CRITERIA FOR USE OF STABILITY AUGMENTATION DEVICES

AUGMENTATION USE	LIMITATION
TO OVERCOME AIRFRAME STATIC INSTABILITY	REQUIRES USE OF LESS THAN 50% AVAILABLE CONTROL-SYSTEM TRAVEL DURING SPECIFIED MANEUVERS
TO OVERCOME UNSTABLE DAMPING	AMOUNT OF UNSTABLE DAMPING MOMENT OF BASIC AIRFRAME SHOULD BE LESS THAN 50 % OF THE RESULTING STABLE DAMPING MOMENT

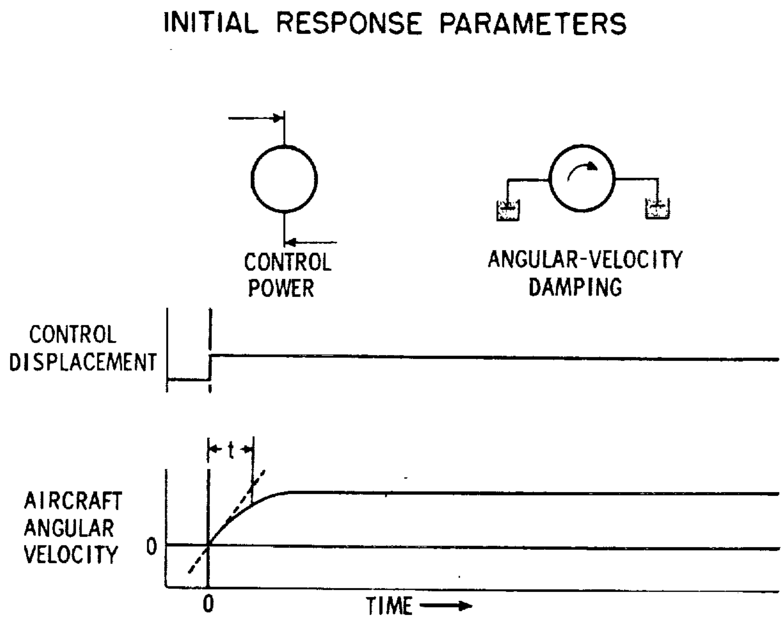

Figure 1

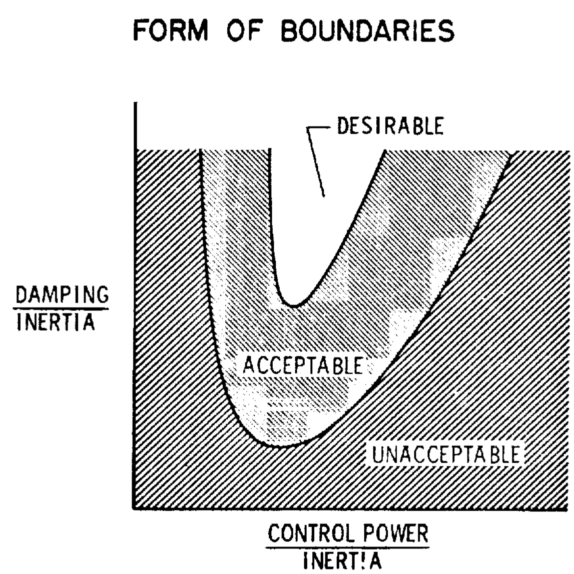

Figure 2

VARIATION OF RESPONSE PARAMETERS WITH AIRCRAFT SIZE

ANGULAR DISPLACEMENT, $A/\sqrt[3]{W+1000}$

DAMPING/INERTIA, $B(I)^{-0.3}$

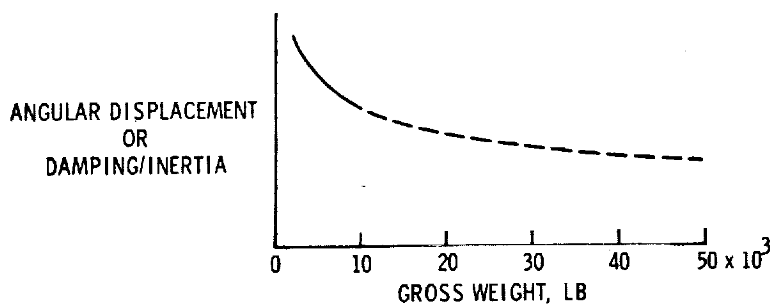

Figure 3

VARIATION OF SIDE FORCE DUE TO
YAWING ACCELERATION WITH SIZE

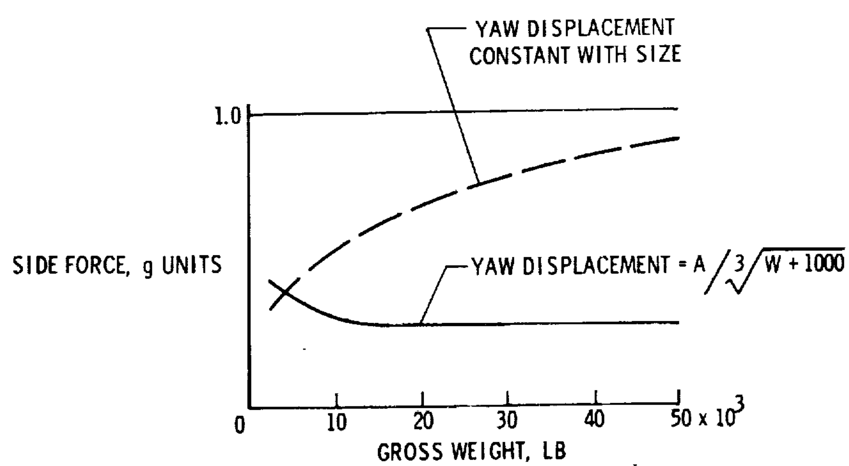

Figure 4