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FLIGHT INVESTIGATION OF V/STOL HEIGHT-CONTROL REQUIREMENTS FOR HOVERING AND LOW-SPEED FLIGHT UNDER VISUAL CONDITIONS

by James R. Kelly, John F. Garren, Jr., and Perry L. Deal

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SUMMARY

As a result of the direct relation which exists between available thrust-weight ratio and payload capability, there is considerable interest in defining, as accurately as possible, the minimum thrust-weight requirements for VTOL operation. The purpose of the present investigation was to refine the hovering results from previous studies and to extend the research coverage to include forward flight. The tests included both precision and maneuvering tasks, under visual conditions, and were conducted with a variable-stability helicopter. Variations were made in maximum thrust-weight ratio, normal-velocity damping, sensitivity of the height-control lever, and time delays in the thrust response.

The results indicated that the task involving acceleration from hover, and the subsequent climbout, imposed a more stringent requirement on thrust-weight ratio than deceleration at the bottom of the approach, which is generally assumed to be the most critical task of all. For normal operations as reflected by the primary evaluation task, the minimum satisfactory level of thrust-weight ratio was 1.09 providing other parameters were within a range which permitted a climb capability of at least 600 feet per minute (3 meters per second). Considering the approach tasks alone, thrust-weight ratios as low as 1.03 were satisfactory if the normal-velocity damping level was equal to or greater than $-0.25 \frac{1}{\text{second}}$.

INTRODUCTION

As a result of the direct relation which exists between available thrust-weight ratio and payload capability, there is considerable interest in defining, as accurately as possible, the minimum thrust-weight requirements for VTOL operation. In an early effort to obtain preliminary information in this area, the NASA conducted studies with a fixed-base simulator and with a limited-motion single-degree-of-freedom simulator (±4 feet (1.2 meters) of vertical translation), references 1 and 2, respectively.

Height-control criteria were further refined in an investigation which employed a single-degree-of-freedom simulator having a vertical-translation capability of 100 feet (30 meters) (ref. 3). Except for the pure hovering case, however, VTOL height-control involves, at the very least, three degrees of freedom – that is, vertical translation, horizontal translation, and pitch angular motion.

The purpose of the present height-control investigation was to extend previous research coverage by including all six degrees of freedom in an actual flight environment. The tests were performed under visual conditions with a variable-stability helicopter and included both precision and maneuvering tasks. Variations were made in maximum thrust-weight ratio, normal-velocity damping, sensitivity of the height-control lever, and time delays in the thrust response. Three pilots participated in the investigation – two NASA research pilots and a U.S. Army test pilot.

The piloting contributions made by Major Thomas C. West of the U.S. Army Aviation Materiel Laboratory, Fort Eustis, Virginia, are gratefully acknowledged.

SYMBOLS AND DEFINITIONS

The units used for the measurements for this investigation are given in both the U.S. Customary Units and the International System of Units (SI). Factors relating the two systems are given in reference 4.

F_{Z_w} normal force proportional to and opposing translational velocity along body Z-axis, $\frac{\text{pounds force}}{\text{foot per second}}$ $\left(\frac{\text{newtons}}{\text{meter per second}}\right)$

F_{Z_δ} normal force per unit displacement of height-control lever, pounds force per inch (newtons per centimeter)

g acceleration due to gravity, 32.2 feet per second^2 (9.8 meters per second^2)

I_X,I_Y,I_Z moment of inertia about X-, Y-, and Z-axis, respectively, slugs-foot^2 (kilograms-meter^2)

M_{X_δ} rolling moment per unit lateral control displacement, $\frac{\text{pounds force-foot}}{\text{inch}}$ $\left(\frac{\text{newtons-meter}}{\text{centimeter}}\right)$

M_{X_p} rolling moment proportional to and opposing rolling angular velocity, $\frac{\text{pounds force-foot}}{\text{radian per second}} \left(\frac{\text{newtons-meter}}{\text{radian per second}}\right)$

M_{Y_δ} pitching moment per unit longitudinal control displacement, $\frac{\text{pounds force-foot}}{\text{inch}} \left(\frac{\text{newtons-meter}}{\text{centimeter}}\right)$

M_{Y_q} pitching moment proportional to and opposing pitching angular velocity, $\frac{\text{pounds force-foot}}{\text{radian per second}} \left(\frac{\text{newtons-meter}}{\text{radian per second}}\right)$

M_{Z_δ} yawing moment per unit pedal displacement, $\frac{\text{pounds force-foot}}{\text{inch}} \left(\frac{\text{newtons-meter}}{\text{centimeter}}\right)$

M_{Z_r} yawing moment proportional to and opposing yawing angular velocity, $\frac{\text{pounds force-foot}}{\text{radian per second}} \left(\frac{\text{newtons-meter}}{\text{radian per second}}\right)$

M_{Z_v} yawing moment proportional to sideward component of velocity, $\frac{\text{pounds force-foot}}{\text{foot per second}} \left(\frac{\text{newtons-meter}}{\text{meter per second}}\right)$

m mass of aircraft, slugs (kilograms)

p rolling angular velocity, radians per second

q pitching angular velocity, radians per second

r yawing angular velocity, radians per second

$(R/C)_{max}$ maximum rate of climb, feet per minute (meters per second)

T/W thrust-weight ratio, maximum normal acceleration in g units for full-control displacement

u component of velocity along body X-axis, feet per second (meters per second)

v	component of velocity along body Y-axis, feet per second (meters per second)
w	component of velocity along body Z-axis, feet per second (meters per second)
δ	control displacement, inches (centimeters)
θ	pitch angle, radians
ϕ	roll angle, radians

Sensitivity of height-control lever	normal acceleration per unit displacement of height-control lever, F_{Z_δ}/m, g units per inch (g units per centimeter)
Normal-velocity damping	normal acceleration proportional to and, when stable, opposing translational velocity along body Z-axis (negative when stable), F_{Z_w}/m, $\frac{1}{\text{second}}$

Dots over a symbol indicate a time derivative with respect to that parameter; for example, $\dot{q} = \frac{dq}{dt}$ or pitch angular acceleration.

EQUIPMENT AND PROCEDURE

Test Vehicle and Simulation Technique

The variable-stability helicopter shown in figure 1 was used for this investigation. The pilot's control system consisted of: a center stick for pitch and roll control, pedals for directional control, and a collective-type lever for height control. The height-control lever measured 18 in. (46 cm) from the floor-mounted pivot to the hand grip, had an available travel of 42°, and was provided with an adjustable friction device. The computer-model simulation technique was employed for the vertical degree of freedom and for the three angular degrees of freedom. This simulation technique tends to eliminate the effects of external disturbances and the inherent characteristics of the basic aircraft, so that the effects of individual parameters may be conveniently and

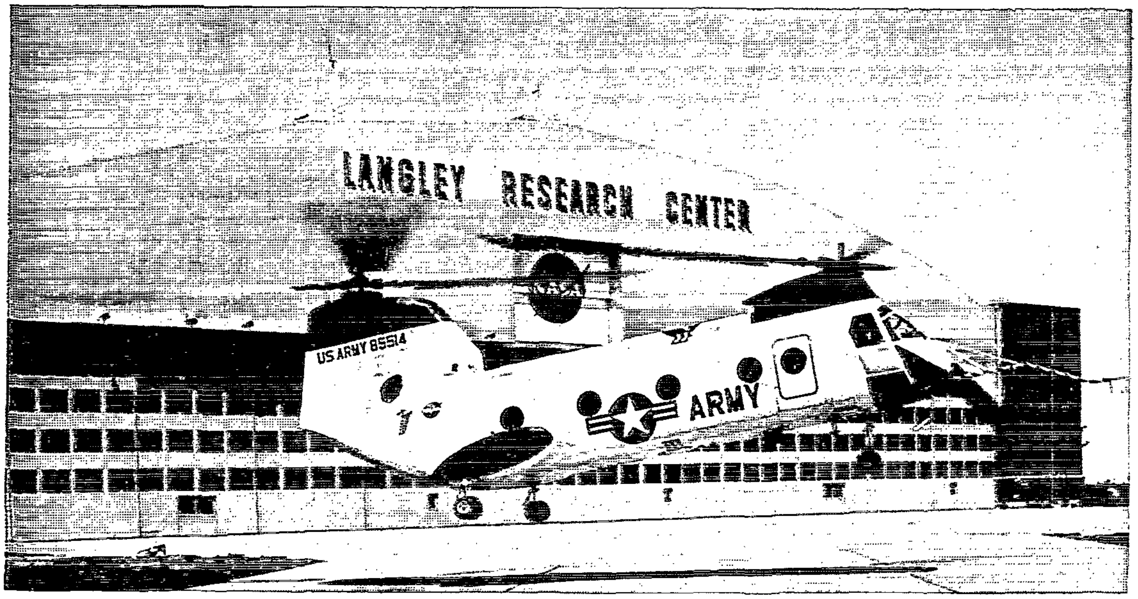
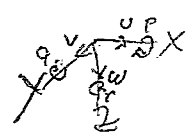


Figure 1.- Variable-stability helicopter. L-64-2891

systematically investigated. Briefly, in the computer-model simulation technique, the equations of motion, which represent the simulated aircraft (or model), are programed into onboard analog computers. Based on the pilot control motions and the programed characteristics, the computer generates a continuous real-time solution which represents the model response. The response of the model aircraft is compared with the actual response of the variable-stability helicopter in order to form an error signal. Through the use of standard servo techniques, the error signal forces the test vehicle to duplicate the response of the model. A more detailed description of the application of the model simulation technique to the rotational degrees of freedom is given in reference 5; for the vertical degree of freedom, in the appendix. The equations for the four independent degrees of freedom used in this investigation (employing a right-hand coordinate system with Z positive downward) are

$$\dot{q} = \frac{M_{Y_\delta}}{I_Y}\delta + \frac{M_{Y_q}}{I_Y}q$$



$$\dot{p} = \frac{M_{X_\delta}}{I_X}\delta + \frac{M_{X_p}}{I_X}p$$

$$\dot{r} = \frac{M_{Z_\delta}}{I_Z}\delta + \frac{M_{Z_r}}{I_Z}r + \frac{M_{Z_v}}{I_Z}v$$

$$(\dot{w} - uq + vp) = g \cos\theta \cos\phi - g\frac{F_{Z_\delta}}{m}\delta + \frac{F_{Z_w}}{m}w$$

The associated stability and control parameters are as follows:

$\frac{M_{Y_\delta}}{I_Y}, \frac{M_{X_\delta}}{I_X}, \frac{M_{Z_\delta}}{I_Z}$ . . . . $0.2\ \frac{\text{rad/sec}^2}{\text{in.}}\ \left(0.079\ \frac{\text{rad/sec}^2}{\text{cm}}\right)$

$\frac{M_{Y_q}}{I_Y}, \frac{M_{X_p}}{I_X}, \frac{M_{Z_r}}{I_Z}$ . . . . $-1.0\ \frac{1}{\text{sec}}$

$\frac{M_{Z_v}}{I_Z}$ . . . . $0.004\ \frac{\text{rad/sec}^2}{\text{ft/sec}}\ \left(0.013\ \frac{\text{rad/sec}^2}{\text{m/sec}}\right)$

$\frac{F_{Z_\delta}}{m}$ . . . . $0.1 \text{ to } 0.6\ \frac{g}{\text{in.}}\ \left(0.04 \text{ to } 0.24\ \frac{g}{\text{cm}}\right)$

$\frac{F_{Z_w}}{m}$ . . . . $0 \text{ to } -1.0\ \frac{1}{\text{sec}}$

The stability characteristics for the two remaining degrees of freedom corresponded to the test vehicle basic characteristics. The stability characteristics for the angular degrees of freedom were selected, on the basis of previous studies, to produce good handling qualities so as not to detract from the pilot's evaluation of the height control.

Test Parameters

Thrust-weight ratio and sensitivity.- Variations in height-control sensitivity were accomplished by electronic gain changes in the computer program. In addition, in order to insure an accurate simulation of the maximum available thrust-weight ratio, an electrical limiting process was employed within the computer program. The full-up position of the height-control lever corresponded to the maximum available thrust-weight ratio being simulated; thrust-weight ratio variations were accomplished by varying the hover position of the height-control lever. Since a flat power-required curve was simulated, the maximum available thrust-weight ratio was independent of forward speed and height above the ground.

Normal-velocity damping.- Normal-velocity damping produces a force which is proportional to and opposes translational velocity along the aircraft body Z-axis. Velocity along the body Z-axis occurs, not only during vertical flight, but also during other maneuvers as well; one such maneuver being a nose-up pitch motion during forward flight which rotates the body Z-axis into the velocity vector. The normal-velocity damping, in opposing this component of forward velocity, produces an increase in thrust which causes the aircraft to flare. The magnitude of the normal velocity damping term is therefore directly related to the aircraft flare capability. For pure hovering flight, the reciprocal of the normal-velocity damping term represents the time required to reach 63 percent of the steady-state vertical velocity following a step input of the control. During the current investigation, the normal-velocity damping was varied from 0 to $-1.0 \frac{1}{\text{sec}}$, which range, as shown in figure 2, includes all existing VTOL types.

Z_w

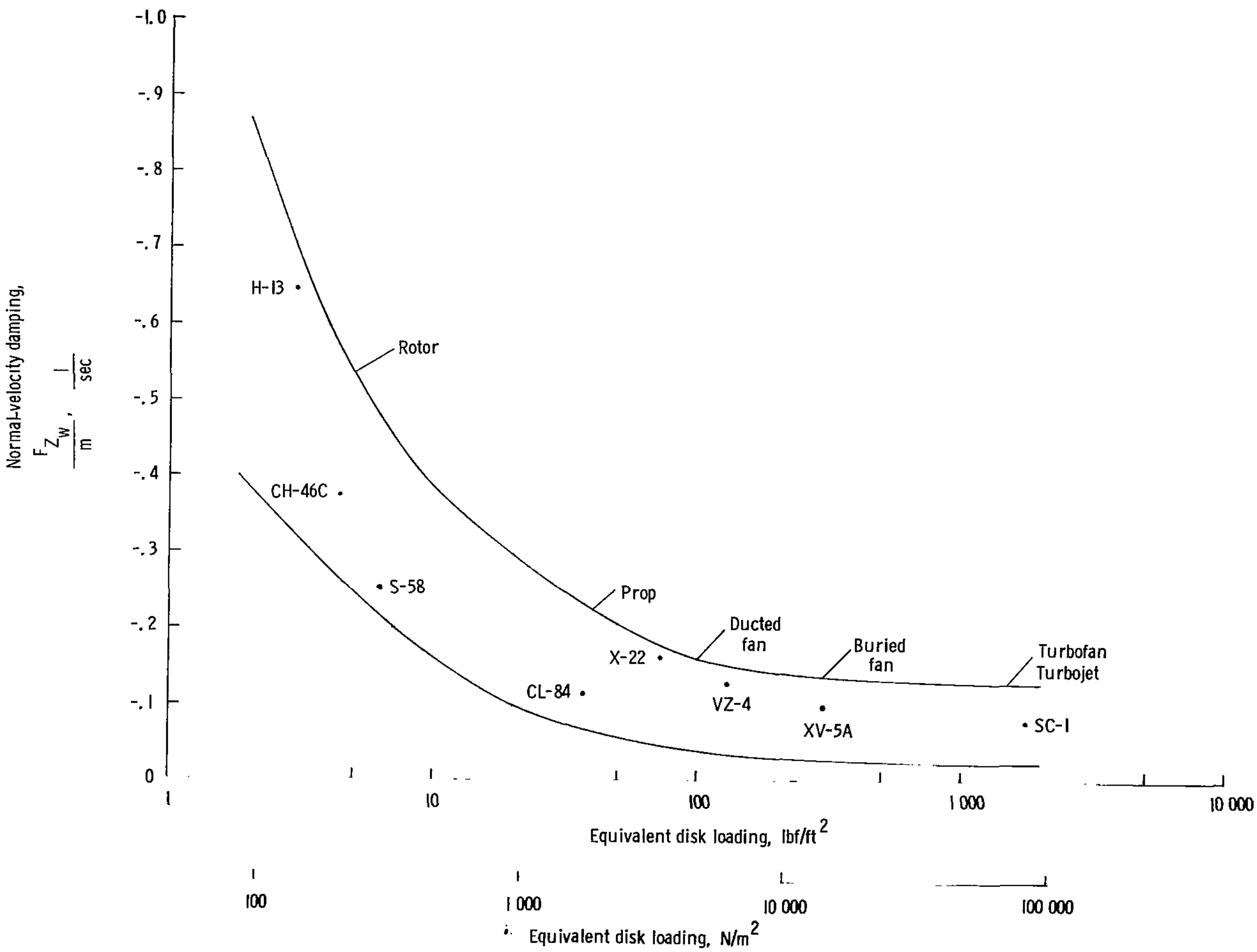


Figure 2.- Variation of normal-velocity damping with disk loading.

Lifting-system time delays.- The effect of a lifting-system time delay (a delay in the vertical-acceleration response to a control input) was studied by electrically modifying the control input with a network which introduced a first-order time delay. The time specified for the delay represents the time required for the thrust to reach 63 percent of the level commanded by the pilot. During the present investigation, time delays from 0.1 to 1.5 sec were evaluated. It should be noted that these time delays include the effective 0.1-sec time delay of the basic aircraft.

Task

The entire investigation was conducted under visual flight conditions. The primary evaluation task began with a rapid transition from hover to forward flight; climbout to 400 ft (122 m); a race-track pattern at 45 knots; and a straight-in approach at approximately a 500-ft/min (2.5 m/sec) descent rate (approximately 6°), terminating in a 50-ft (15 m) hover at the starting point. In addition, approaches were performed at the pilot's discretion using descent rates of 200 to 300 ft/min (1.0 to 1.5 m/sec) for a shallow approach and 800 to 1000 ft/min (4 to 5 m/sec) for a steep approach. It should be noted that these rates of descent were used only as target values in establishing the selected approach path. The actual rate of descent varied somewhat during the latter stages of the approach since the pilot was aiming for a preselected landing pad. Prior to performing the primary task described above, the pilot explored the characteristics of each new test configuration by performing selected secondary tasks such as precision hovering, hovering step inputs of the height-control lever, step altitude changes in a hover, vertical touchdowns, approach to run-on landings, quick starts and stops, and maneuvering flight in close proximity to the ground.

RESULTS AND DISCUSSION

During the initial tests, variations were made in the hover position of the height-control lever in order to establish its significance as a potential test parameter. These tests indicated that the pilot was not sensitive to variations in this parameter; consequently, it was concluded that the full-up control stop could remain fixed, with variations in the maximum thrust-weight ratio being accomplished by simply altering the height-control-lever position for the 1g hovering condition. The initial tests also provided information concerning a suitable height-control sensitivity for use during the rest of the flights. Next, various combinations of maximum available thrust-weight ratio and normal-velocity damping were simulated and, finally, time delays in the thrust response were simulated for selected combinations of the other parameters.

Height-Control Sensitivity

In order to permit the pilot to evaluate variations in height-control sensitivity without being limited by acceleration capability, the maximum thrust-weight ratio was fixed at a sufficiently high value (1.25) so as not to be a limiting factor. Similarly, the normal-velocity damping was fixed at a moderately stable level $\left(-0.25 \frac{1}{\text{sec}}\right)$. The results obtained from the sensitivity variations are shown in figure 3 as a plot of pilot rating (table I) against sensitivity. This figure indicates a best tested sensitivity range of 0.1 to 0.2 g/in. (0.04 to 0.08 g/cm), within which range the control seemed comfortable and natural. At lower sensitivities, below 0.1 g/in. (0.04 g/cm), the pilots complained of excessively large control motions and difficulty in establishing the 1g thrust condition for hovering. For sensitivity values above 0.3 g/in. (0.12 g/cm), the pilots felt it was necessary to exercise extreme care in order to avoid overcontrolling, which, in some systems, could lead to overstressing the lifting-system dynamic components. The maximum value simulated, 0.6 g/in. (0.24 g/cm), was sufficiently sensitive to give the pilot the impression of a pressure control; that is, the control motions were sufficiently small to be imperceptible to him. As a result of these tests the sensitivity was held constant at 0.1 g/in. for the rest of the investigation.

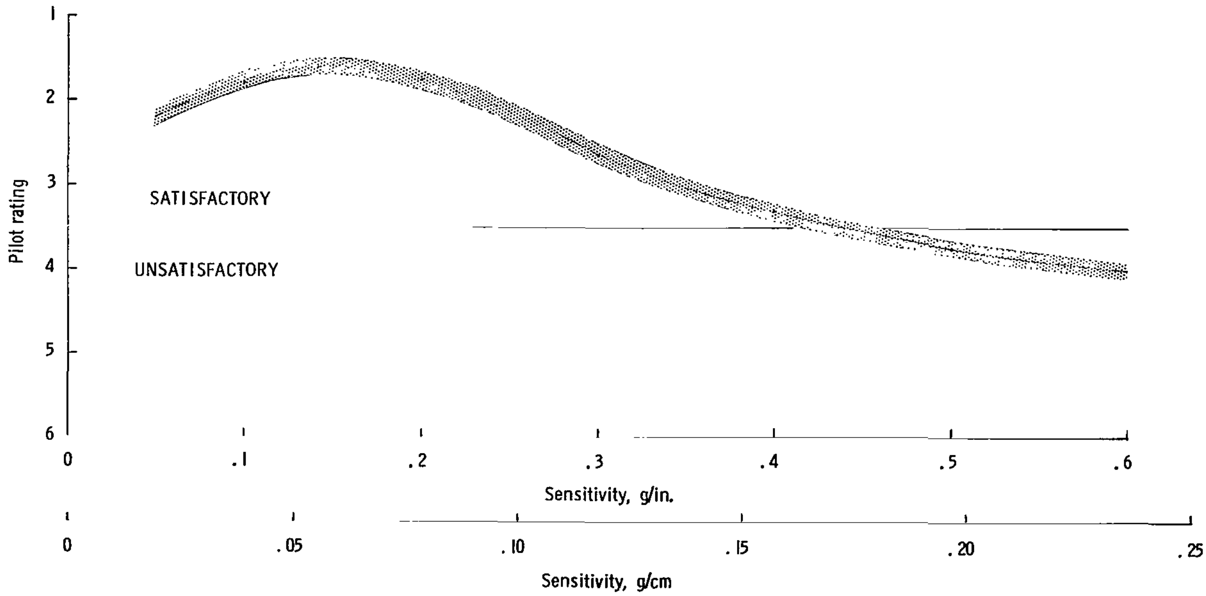


Figure 3.- Variation of pilot rating with control sensitivity. $\frac{T}{W} = 1.25$; $\frac{F_{Z_W}}{m} = -0.25 \frac{1}{\text{sec}}$.

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[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.

Thrust-Weight Ratio and Damping

Previously, it has been assumed that the requirement for arresting descent rates at the bottom of the approach represented the most critical task from the standpoint of defining satisfactory minimums for thrust-weight ratio. (For instance the AGARD recommendations for V/STOL handling qualities, ref. 6, specifies a greater thrust-weight ratio for landing than for take-off.) In the present investigation, however, the acceleration from hover to forward flight, together with the need for an adequate climb capability, placed the highest premium on thrust-weight ratio. Since there might still exist special circumstances wherein the descent results would be of the greater interest, the results for each of these two tasks are treated separately. As a matter of additional interest, the pilot ratings and comments indicated that the quick-start-and-stop maneuver provided a brief task which contained the critical elements of both the descent and the acceleration portions of the primary evaluation task, and, for future work, could reasonably be used in lieu of the lengthier tasks.

Acceleration and climb capability.- The thrust-weight ratio and damping results which were obtained from the acceleration and climbout task are presented in figure 4.

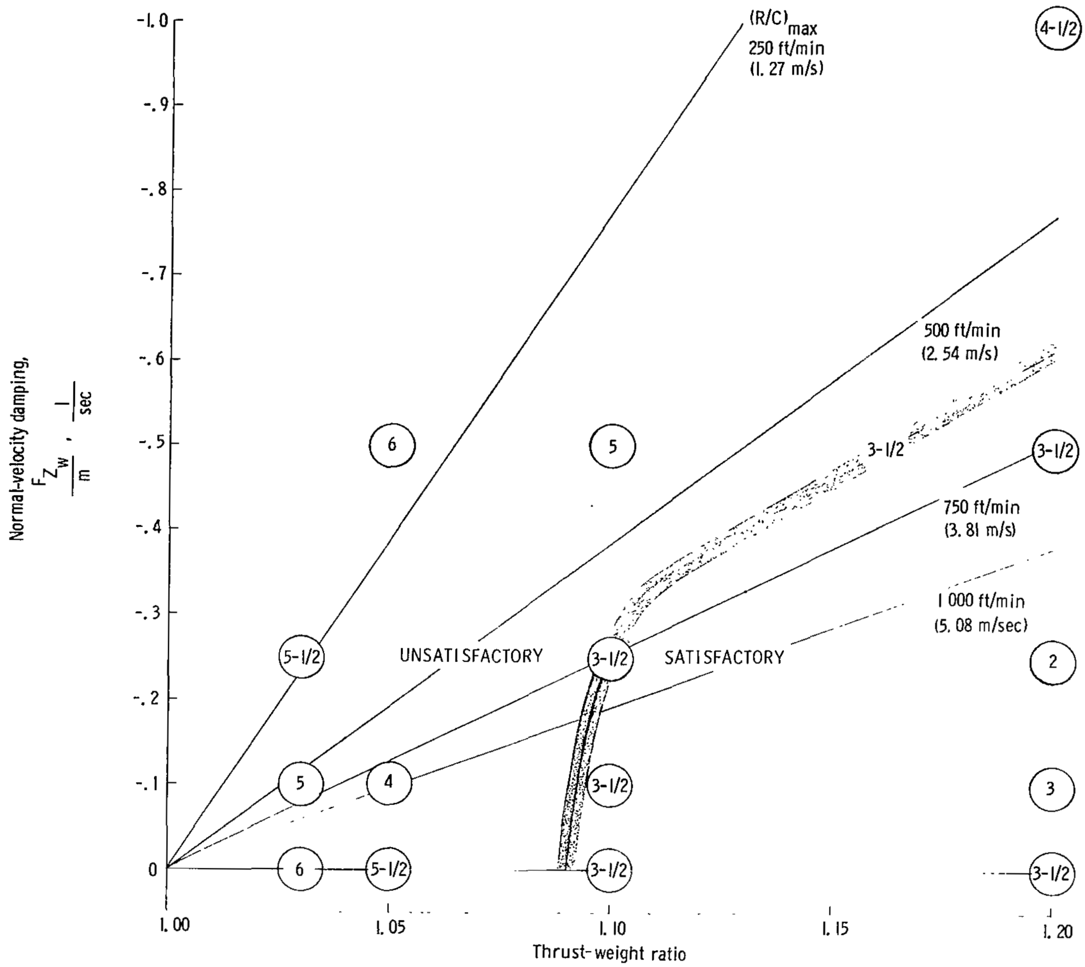


Figure 4.- Combinations of thrust-weight ratio and damping required to provide a satisfactory acceleration and climb capability.

In addition to averaged pilot ratings and a pilot-rating boundary for minimum satisfactory characteristics $\left(\text{a pilot rating of } 3\frac{1}{2}\right)$, the figure includes lines of constant rate-of-climb capability. Although the pilots had widely differing backgrounds, their results were in close agreement with respect to the acceleration and climb capability required for normal operation (i.e., normal operation as reflected by the primary task). Figure 4 indicates that for normal operations, thrust-weight ratios as low as 1.09 were satisfactory, provided a rate-of-climb capability of at least 600 ft/min (3 m/sec) existed. For thrust-weight ratios less than 1.09 a restriction was encountered in the form of insufficient acceleration capability. For example, even though the rate-of-climb capability of the four test combinations in the lower left-hand corner of the figure actually equals or exceeds 600 ft/min, they were rated unsatisfactory because of the excessive time required and, consequently, the space required for establishing a desired combination of airspeed and climb rate.

As a matter of interest, level-flight acceleration capability has been plotted against thrust-weight ratio in figure 5. This figure applies to systems which rely only on tilting the thrust vector to produce translational accelerations. For a thrust-weight ratio of 1.09, figure 5 indicates that a level-flight acceleration (or deceleration) capability of about 0.43g would exist. In the general case the available thrust-weight ratio must simultaneously provide the thrust requirements for an accelerating transition involving a climbing banked turn. It was with this maneuver in mind that the pilot downrated the poor acceleration characteristics associated with thrust-weight ratios less than 1.09.

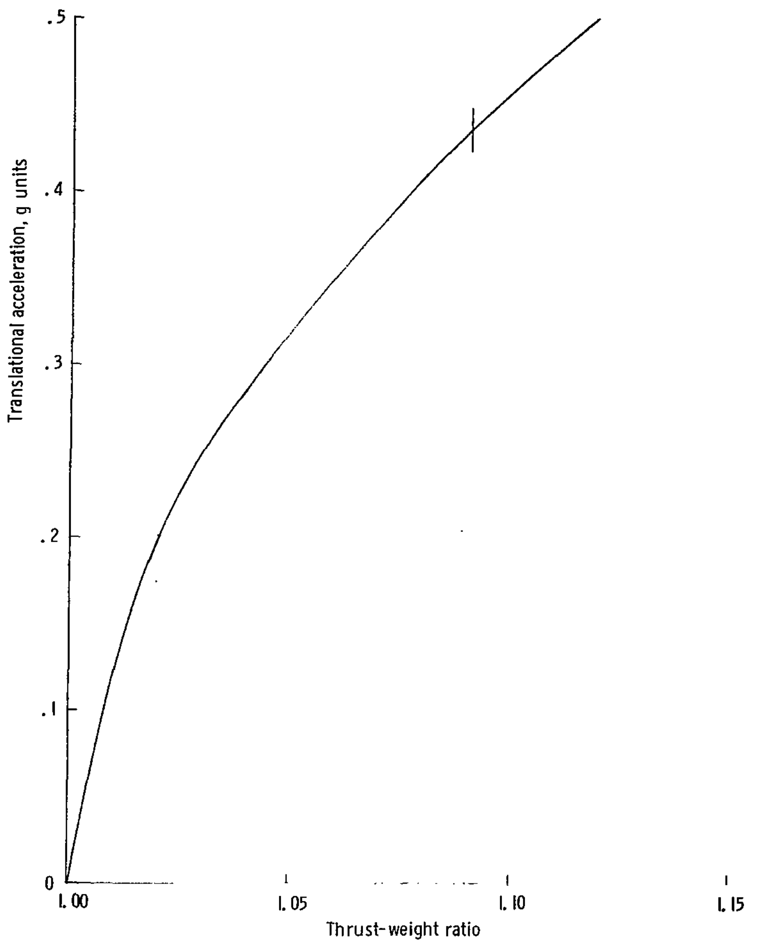


Figure 5.- Effect of thrust-weight ratio on level-flight acceleration capability.

Arresting descent rates.- The results obtained while arresting the descent rate at the bottom of the approach are shown in figure 6, in which averaged pilot ratings are presented for the test combinations of thrust-weight ratio and normal-velocity damping. A pilot-rating boundary for minimum satisfactory characteristics is located on the figure. For test combinations within the satisfactory region the pilot was able to comfortably judge the altitude at which he should begin arresting the descent rate. In other words, for these conditions, a sufficient thrust margin (installed thrust plus thrust due to damping) existed such that the pilot was not committed to a landing following his initial decision.

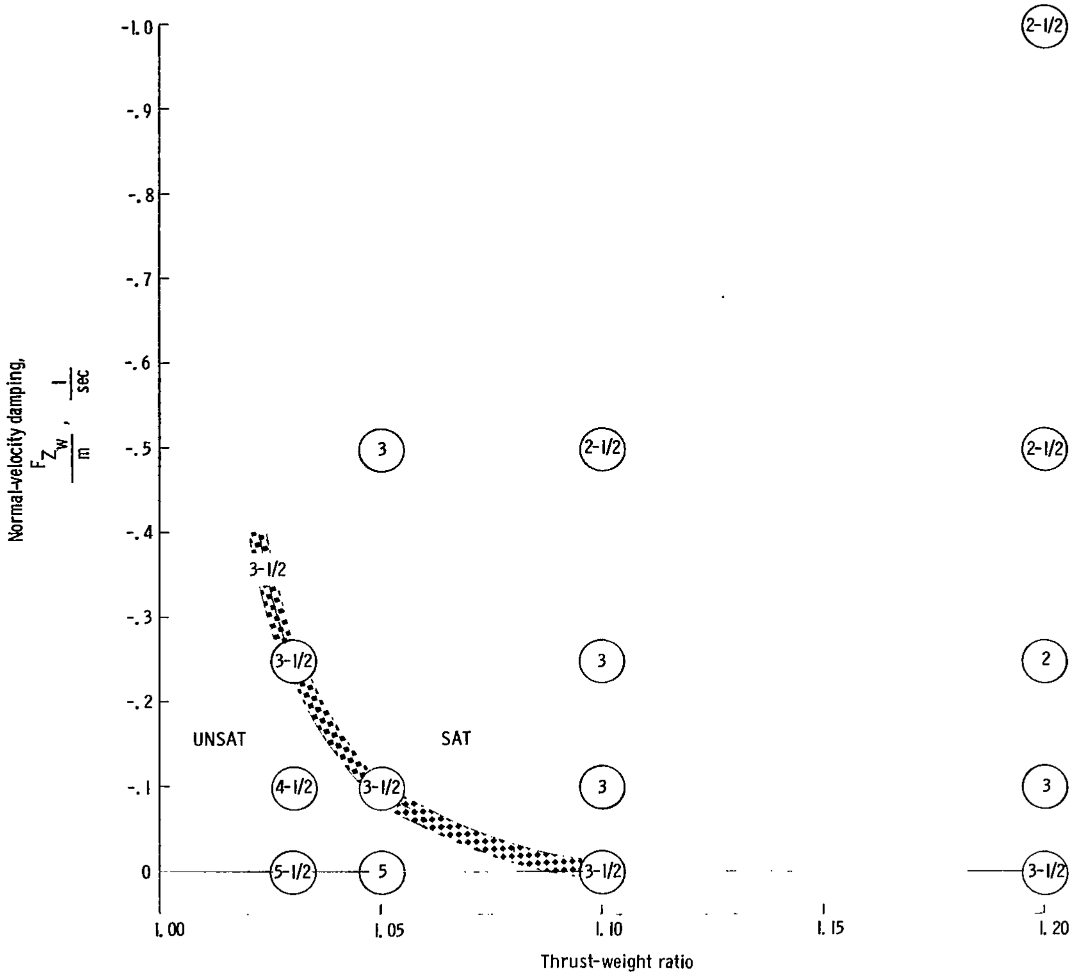


Figure 6.- Combinations of thrust-weight ratio and damping required to provide a capability for satisfactorily arresting the descent rates.

As might be expected for this task, a substantial trade-off existed between the damping and the required thrust-weight ratio. For example, increasing the damping level from 0 to $-0.25 \frac{1}{\sec}$ permitted a decrease in thrust-weight ratio from 1.09 to 1.03. As indicated previously, damping provides a flare capability; therefore, when additional thrust was needed for the final deceleration at the bottom of the approach, the damping enabled the pilot to trade forward speed for the required thrust by simply rotating the aircraft. Also, in pure vertical flight, the damping is effective in slowing the descent rate.

Additional considerations.- The simulation technique which was employed in this investigation permitted the simulation of a flat power-available curve. In other words, the maximum available thrust-weight ratio was independent of forward speed. This characteristic is representative of jet VTOL types while they are operating in the low-speed range before conversion to wing-borne flight. The results, therefore, can be applied directly to jet VTOL aircraft and, with proper treatment, can be applied to aircraft which have significant variations in their power-required curves (e.g., rotary wing types) by treating a change in power required as an appropriate change in thrust-weight ratio. The influence of ground proximity on the available thrust-weight ratio may be treated in a similar manner. The results of this investigation may be somewhat conservative when applied to rotary-wing type vehicles where stored energy effects are present, which can provide additional thrust for short time intervals.

Lifting System Time Delay

The results of the time-delay variations are presented in figure 7 as a plot of pilot rating against the time-delay parameter. For comparison purposes the results from reference 3 are also indicated in the figure. The figure indicates that the trends obtained during both investigations are very similar; the slightly better pilot ratings obtained during the present investigation for a given time delay can be accounted for by the difference in the damping levels between the two studies. (See insert in fig. 7.) Based on the degree of correlation which existed with the previous results, it was concluded that an extensive investigation in this area was not warranted.

The presence of the time delay was considered to be most objectionable during the landing attempts, which, being a precision task, normally requires the pilot to increase his control activity as wheel height is reduced. The time delays presented relatively little problem for operation at higher altitudes. Although the pilot was able to maintain control of the aircraft for even the largest time delays simulated, for time delays greater than 0.5 sec, he found it necessary to alter his normal control technique for landing in order to reduce overcontrolling to a point where a reasonably safe touchdown could be made. One of these techniques involved terminating the approach in a hover at the normal altitude (50 ft (15 m)), from which a constant, low sink rate was established and flown unchecked until contact with the ground. In the other technique the pilot shifted to a dither method wherein he continuously cycled the height-control lever at a frequency of about 3 cps and a double amplitude of about 0.6 in. (1.5 cm). Although both of these techniques, permitted the pilot to cope more satisfactorily with time delays above 0.5 sec, it was considered unlikely that such techniques would be as beneficial when coupled with disturbances such as can be encountered near the ground with some VTOL configurations. Furthermore, the use of the dither technique was very tiring to the pilot, and both techniques could increase fuel consumption.

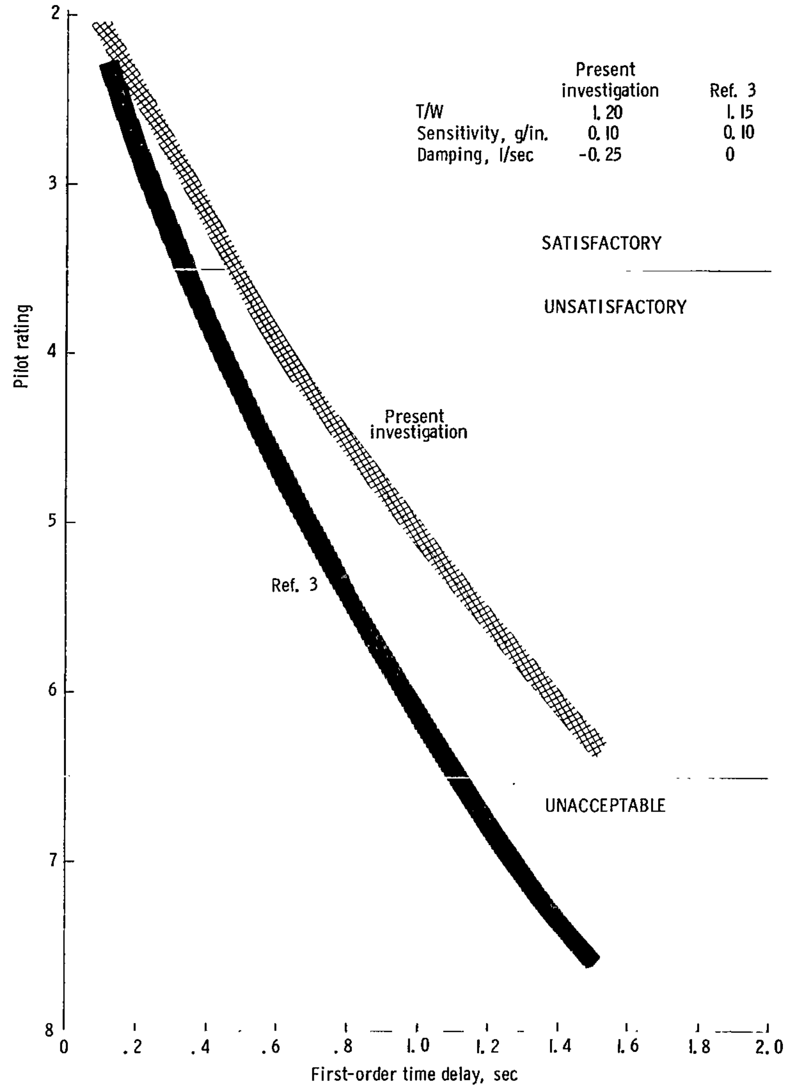


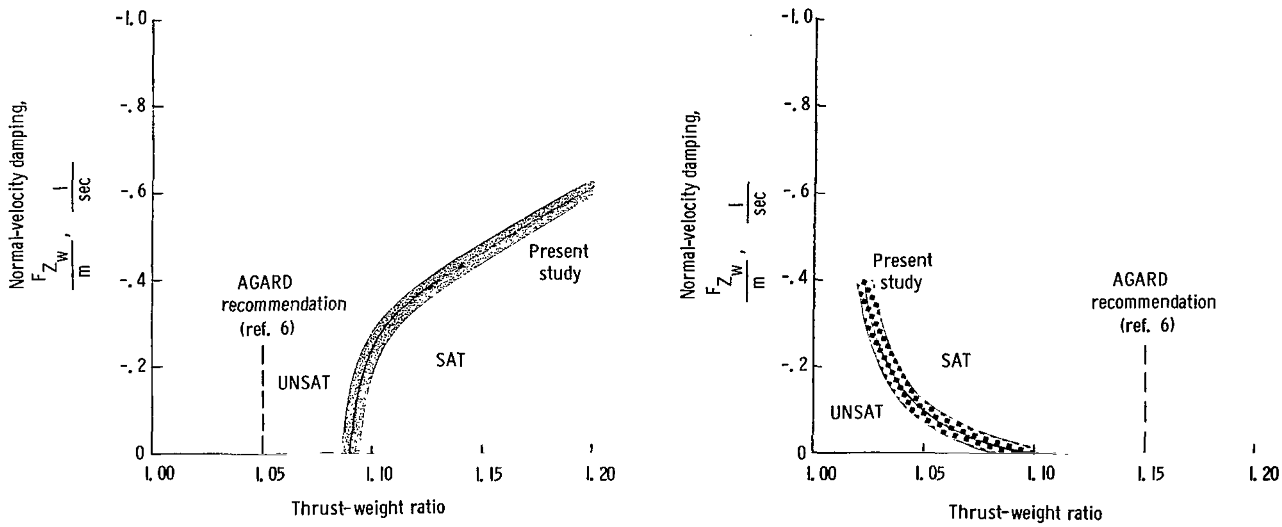
Figure 7.- Variation of pilot rating with thrust response time delay for vertical touchdowns.

It was discovered during the tests that the presence of a meter, which displayed position of the height-control lever for setting up the test conditions, greatly enhanced the pilot's ability to cope with even the largest time delays and enabled the use of more normal control techniques. Having once noted the sensitivity of the meter to motions of the controller and the approximate indication for steady hovering, the pilot was able to derive lead-information from the meter which compensated, in part, for the lack of motion cues in the delayed response. It should be noted, however, that the results presented in figure 7 were obtained without benefit of the meter.

Comparison With Current Criteria

AGARD recommendations for V/STOL handling qualities (ref. 6) suggest that the optimum control sensitivity is on the order of 0.15 g/in. (0.06 g/cm) of control movement. Reference to figure 3, which presents the variation of pilot rating with control sensitivity, indicates that the AGARD recommendation would lie in the center of the best tested region of the present investigation.

In figures 8(a) and 8(b), the thrust-weight ratio results from the present investigation are compared with corresponding AGARD recommendations. In making the comparison, it has been assumed that the take-off requirement of reference 6 corresponds to the acceleration and climb results of the present study and, further, that the landing requirement of reference 6 corresponds to arresting descent rates at the bottom of the approach. Inspection of these two figures indicates that reference 6 requires a much greater thrust-weight ratio for landing than for take-off. This is seen to be contrary to the results of the present investigation which, except for zero damping, always requires a greater thrust-weight ratio for acceleration and climbout (i.e., the take-off) than for arresting descent rates (i.e., the landing); for zero damping, the thrust-weight requirements of the present investigation are identical for the two tasks. It is concluded from these tests, therefore, that the requirement for an adequate acceleration and climb capability places the greatest demand on thrust-weight ratio. It is recognized, of course, that the minimum satisfactory thrust-weight ratio for the acceleration and climbout task would vary somewhat with specific mission constraints such as field size, exposure time, and the height of surrounding obstacles. Caution should be exercised, therefore, in applying the present acceleration and climb results to operations wherein the specific



(a) Acceleration and climb task.

(b) Arresting rate-of-descent task.

Figure 8.- Comparison of thrust-weight results with current criteria.

mission constraints are either much more or much less stringent than those represented by the primary evaluation task; the present task might be considered as corresponding to a transport-type operation.

Reference 6 recommends that thrust time delays should not exceed 0.3 sec. Figure 7 indicates that a time delay of this magnitude would result in a control degradation of approximately 1 pilot-rating unit for the touchdown portion of the landing. This rapid degradation in controllability indicates that time delays of an appreciable magnitude can be tolerated only for control characteristics which are otherwise near optimum.

CONCLUSIONS

A flight investigation of height-control requirements for VTOL aircraft was conducted with a variable-stability helicopter under visual conditions. The primary evaluation task began with a rapid transition from hover to forward flight, a race-track pattern at an altitude of about 400 ft (122 m), and a straight-in approach (using approximately a 500-ft/min (2.5 m/sec) rate of descent) terminating in a 50-ft (15 m) hover at the starting point. Based on the results of this investigation, the following conclusions are drawn:

1. Acceleration from hover and the subsequent climbout impose the most stringent requirement on thrust-weight ratio.

2. For normal operations, as reflected by the primary evaluation task, the minimum satisfactory level of thrust-weight ratio is 1.09, providing other parameters are within a range which permits a climb capability of at least 600 ft/min (3 m/sec).

3. Considering only the approach task, including a flare and landing, satisfactory operation is possible for thrust-weight ratios as low as 1.03 if the normal-velocity damping level is equal to or greater than $-0.25 \frac{1}{\text{sec}}$.

4. The results obtained for variations in thrust time delay are in good agreement with previous investigations, which employed ground-based motion simulators, and indicate landing to be the critical task for assessing time delays.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 17, 1967,
721-04-00-01-23.

APPENDIX

APPLICATION OF THE COMPUTER-MODEL TECHNIQUE TO THE VERTICAL DEGREE OF FREEDOM

The application of the model simulation technique relies on the use of one or more error signals (i.e., the difference in the commanded response and the actual response) to force the test vehicle. For the rotational degrees of freedom, angular velocity is generally selected as the basis for formulating the error signal. For the translational degree of freedom, the error signal may be formulated as follows. The following equation represents the translational response along the body Z-axis:

$$(\dot{w} - uq + vp) = g \cos \theta \cos \phi - g \frac{F_{Z_\delta}}{m} \delta + \frac{F_{Z_w}}{m} w \tag{1}$$

Rearranging the terms in equation (1) gives

$$(\dot{w} - uq + vp) - g \cos \theta \cos \phi = - g \frac{F_{Z_\delta}}{m} \delta + \frac{F_{Z_w}}{m} w \tag{2}$$

which suggests a means for formulating an error signal. The left-hand side of equation (2) is recognized as representing the output of an accelerometer, which has its sensitive axis alined with the aircraft body Z-axis (i.e., a normal accelerometer); the right-hand side represents the net force, excluding gravity, acting on the aircraft along the body Z-axis. It is thus possible to generate an error signal by comparing the output of a normal accelerometer with a voltage which is proportional to the sum of the terms given on the right-hand side of the equation.

The essential features of the overall simulation mechanization are shown in figure 9. Since location of the accelerometer at the aircraft center of gravity was not feasible, appropriate corrections to the accelerometer output were performed in the computer.

The normal-velocity signal, w, employed in the simulation was obtained from a Doppler radar system which senses the aircraft velocity along the three body axes. The velocity signals from the Doppler radar system were corrected for the location of the radar system antenna with respect to the aircraft center of gravity.

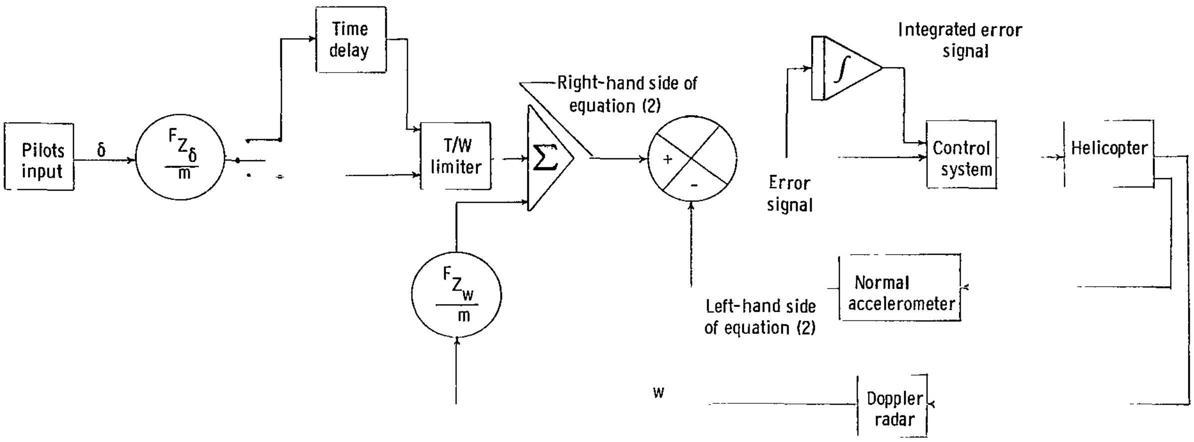


Figure 9.- Simplified signal-flow diagram for the vertical degree of freedom.

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