Handling Qualities Research at the National Aeronautical Establishment, Ottawa, Using Airborne V/STOL Simulators

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A brief description of the two V/STOL aircraft simulators operated by the National Aeronautical Establishment will be presented. One of these variable stability helicopters has the capability of varying its characteristics in the three rotational degrees of freedom over wide limits and has been flying for several years. The other uses the same basic "model-controlled" method of simulation but has many improvements including the capacity to alter its response in the vertical or heave degree of freedom. These aircraft have been used for general research into V/STOL handling qualities requirements and for simulation of particular aircraft. An investigation into the effects of weathercock stability on directional handling qualities during both visual and simulated instrument flying tasks illustrated the pilots' desire for higher levels of angular rate damping while flying on instruments. A simulation of a tilt-wing V/STOL aircraft, the Canadair CL-84, indicated maximum satisfactory and acceptable levels of backlash and flexibility in the flight control systems with the stability augmentation system fully operative and following a variety of selected failures.

Nomenclature

a = pilot's lead time constant, sec
B_1 = backlash between the pilot's height control and the engine power lever, degrees of engine power lever
B_2 = backlash in positioning of main rotor blade angle, deg
K_p = pilot's gain
m = mass, slug
N_r = angular rate damping in yaw, (rad/sec²)/(rad/sec)
N_v = weathercock stability parameter based on sideslip velocity, (rad/sec²)/fps
N_β = weathercock stability parameter based on sideslip angle, (rad/sec²)/rad
N_{δ_r} = control sensitivity in yaw, (rad/sec²)/in.
$p, \dot{\phi}$ = angular rate of roll, rad/sec
$q, \dot{\theta}$ = angular rate of pitch, rad/sec
$r, \dot{\psi}$ = angular rate of yaw, rad/sec
s = Laplace operator
T = thrust, lb
v_g = side velocity due to lateral gusts, fps
w = vertical perturbation velocity, fps
w_m = vertical perturbation velocity from model, fps
Z_w = vertical damping, (ft/sec²) fps
β = sideslip angle, rad
δ_c = height control deflection, in.
δ_r = yaw control deflection, in.
∂ = indicates partial derivative
σ_δ = rms value of pilot's directional control movements, in.
σ_ψ = rms value of heading response, rad
τ = pilot's reaction time lag, sec
θ = engine power lever position, deg
$\dot{\theta}_m$ = angular pitch rate of model, rad/sec
W = aircraft weight, lb.

I. Introduction

DURING the past three years the National Aeronautical Establishment (NAE) has carried out several research programs[1-3] using a light helipcoter as a three degrees-of-freedom V/STOL airborne simulator.[4] Recently, the development of a similar airborne simulator (Fig. 1) was completed incorporating many improvements including the ability to vary the flight characteristics in the vertical or heave degree of freedom as well as the three rotational degrees. This aircraft has been used in two investigations to date.[5,6] Both of these aircraft utilize the "model-controlled" method of simulation described in detail in Ref. 7 wherein it is shown that this method has a versatility that compares favorably with that of ground-based simulators in allowing rapid changes in flying characteristics and has many other advantages over alternate types of flight simulators. Figure 2 shows how the electric flying controls, the electrical analog computer, the autopilot, and the helicopter are combined to effect this approach to simulation.

Two pilots occupy the simulators during all tests with the one in the left-hand cockpit acting as safety pilot and program manager by selecting the desired values on the gain setting potentiometers shown in Fig. 3, while the one on the right operates the electric controls and evaluates the characteristics of the model, rating its acceptability by the pilot opinion rating schedule of Ref. 8

Two recently completed programs are discussed. Both general research programs and simulation of particular aircraft can be undertaken with these vehicles, whereas the piloting task may be visual or instrument or a combination of the two. The majority of the completed investigations have been concerned with the determination of the ranges in which selected important parameters have to be set to allow the pilot to control the aircraft under normal or emergency operations while performing some desired task. The work to be reported first is general in nature; it is a comparison of the pilot's ability to perform an approach task under both visual and instrument conditions in the presence of various levels of weathercock stability. Details of this investigation are found in the following sections and in Ref. 9.

The second program to be outlined is a simulation of the Canadair CL-84 tilt-wing aircraft undertaken to assess the influence on the handling qualities of 1) backlash and flexibility in various locations in the control systems and 2) various realistic stability augmentation failures in the presence of these backlashes during a visual hovering and low-speed maneuvering task. The tests were completed before the actual aircraft flew and, in addition to providing the company with positive indications of what backlashes, etc., could be tolerated, thoroughly familiarized the company pilots with the flying and control system characteristics to be expected. The details of this research program may be found in Ref. 6 and a brief description is presented in subsequent sections.

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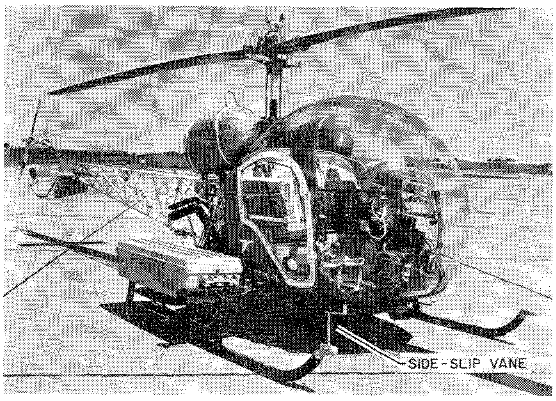

Fig. 1 Four degrees-of-freedom V/STOL simulator.

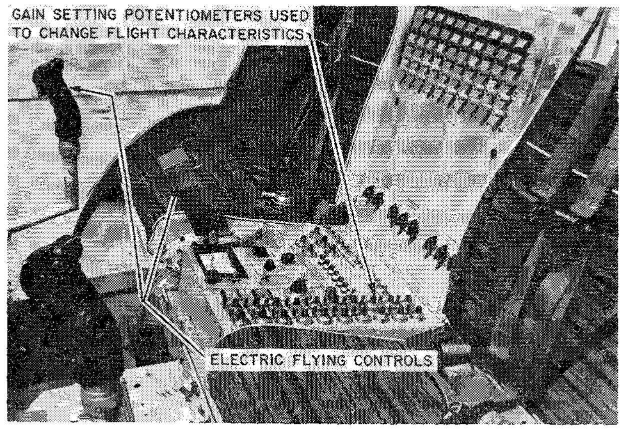

Fig. 3 Cockpit of the simulator.

2. Directional Handling Qualities Required for Visual and Instrument Flight

In order to investigate the effects on directional handling qualities of the task performed by the pilot, the visual flight investigation of Ref. 2 was repeated utilizing an instrument approach task. The directional handling qualities boundaries, plotted as constant pilot opinion contours on directional angular rate damping N_r[(rad/sec^2)/(rad/sec)], directional control sensitivity N_{δ_r}[(rad/sec^2)/in.], planes were determined for three values of weathercock stability N_β[0.5, 1.0, and 1.75(rad/sec^2)/rad] covering the range of this parameter expected to be significant for V/STOL aircraft.

The model-controlled method together with the three degrees-of-freedom simulator described in the previous section were used in this investigation. Lateral turbulence with an rms level of 8.9 fps and a break-point in its frequency spectrum at 0.36 rad/sec was introduced synthetically to disturb the simulator directionally and provided a more realistic flight situation to the pilot. The following sections describe briefly the equations of motion of the "model," the test procedures, and a discussion of the results. A more comprehensive description of this research and the results obtained will be found in Ref. 9.

2.1 Equations of Motion

The electrical analog comprising the model was located in the system, as shown in Fig. 2, and was wired according to the equation of motion of each of the rotational degrees of freedom of the simulated aircraft. All the stability derivatives pertaining to moments are the dimensional derivatives divided by the moment of inertia about the appropriate axis. For example, the directional control sensitivity N_{δ_r} has the dimensions (rad/sec^2)/in. resulting from the actual yawing moment per inch of rudder control (lb-ft/in.) divided by the yawing moment of inertia (slug-ft^2).

The evaluation pilot was responsible for control of all six degrees of freedom of the simulator, but, since this investigation was concerned with the effect of various levels of weathercock stability on the directional handling qualities boundaries, while performing an instrument approach task, the longitudinal and lateral derivatives were held constant at values that produced good flying characteristics about these axes. This procedure is felt to be appropriate since most stability augmentation systems are designed so that any single failure will affect only one channel, leaving all others with their original desirable characteristics.

The longitudinal (pitching) and lateral (rolling) equations of motion were made as simple as practical while still presenting a realistic situation to the pilot and, hence, each contained only two terms: the control sensitivity and angular rate damping. The three variables in this investigation were the weathercock stability N_v or N_β, the directional control sensitivity N_{δ_r}, and the directional rate damping N_r. These derivatives were included in the yawing equation of motion which also introduced realistic disturbances due to synthetic lateral turbulence. The yawing equation of motion was then

$$\ddot{\psi} = N_{\delta_r}\cdot\delta_r + N_r\cdot\dot{\psi} + N_\beta\cdot\beta + N_v\cdot v_g \qquad (1)$$

Figure 4 shows a simplified analog circuit which, when properly scaled, made up the directional model controlling the autopilot in forward flight. The gain setting potentiometers A, B, C, and D shown in the figure were located in the cockpit, as seen in Fig. 3, and were used by the safety pilot to set the levels of directional control sensitivity, damping, and weathercock stability for each model.

Three values of N_β, 0.5, 1.0, and 1.75 (rad/sec^2)/rad, corresponding to the levels investigated during the visual flight program of Ref. 2, were tested together with sufficient combinations of directional control sensitivity and angular rate damping to allow plotting of the pilot iso-opinion curves separating the significant areas of operation.

2.2 Test Procedures

During each flight, the evaluation pilot made approaches with a number of models of varying characteristics and rated his opinion by the scale of Ref. 8. In order to preclude his use of external visual cues during the instrument approach task,

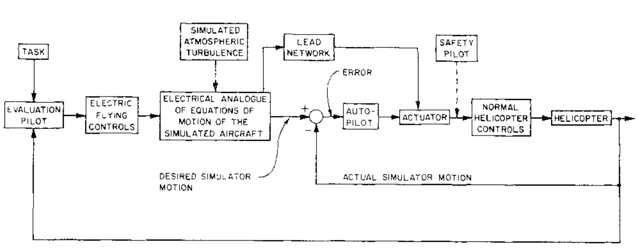

Fig. 2 "Model-controlled" simulation method.

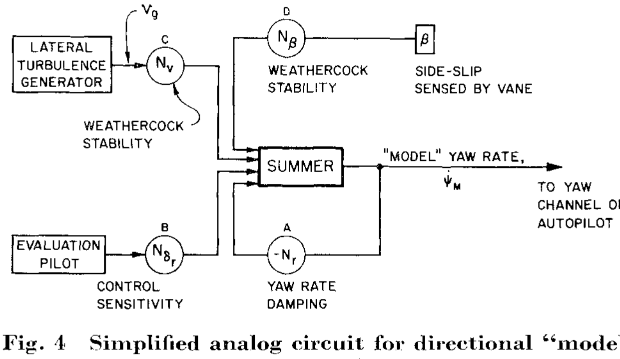

Fig. 4 Simplified analog circuit for directional "model" in forward flight.

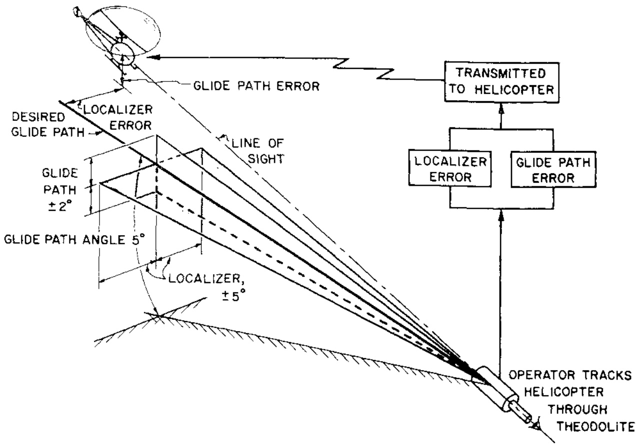

Fig. 5 Synthetic instrument landing system.

an amber-blue hood system was utilized, effectively restricting his vision to the instrument panel.

The instrument landing system (ILS) was chosen as a convenient and meaningful approach aid for the instrument approach task. A synthetic ILS consisting of a theodolite (or tracking telescope), manipulated by an operator and a radio transmitter all situated in a truck, provided the mobility necessary to allow all approaches to be close to the direction of the surface wind. The departures of the helicopter from the desired localizer track and glide path angle were measured by tracking it manually with the theodolite while the airborne ILS receiver, through a cross-pointer-type instrument, indicated these departures to the pilot. Figure 5 illustrates the ILS beam[10] with the glide path set at the approach angle of 5° and the sensitivities for full-scale deflection of the pilot's indicator of ±5° of inbound track and ±2° of glide path. These sensitivities were arrived at by experiment and are not necessarily optimum values, since the objective was to provide a reasonable instrument task and not to determine an ideal V/STOL approach system. The flight pattern followed by the pilots is shown in Fig. 6, where it is seen that the limits of the instrument portion of the approach were 100 ft and approximately $\frac{1}{5}$ naut mile while the approach speed was 45 knots. Early flights demonstrated that instrument approaches at 30 knots, the visual approach speed, were very difficult, because this entailed operating on the "backside" of the power curve. Upon reaching the approach limits, the pilot made visual contact with the ground and flew a side-step or S turn maneuver to simulate a misalignment condition on breakout from cloud and landed approximately 150 ft to one side of the ILS truck. This task conforms reasonably with recent recommendations for V/STOL instrument approach patterns.[11]

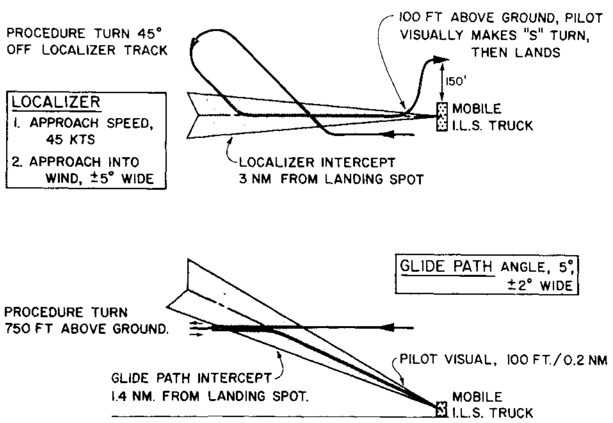

Fig. 6 Instrument approach task.

The visual approach task used in Ref. 2 is summarized in Fig. 7. Briefly, the task consisted of a visual circuit a 500 ft above ground followed by an 11° approach at 30 knots, using the visual approach aid shown, and a landing. Unfortunately, the two tasks could not be flown at the same approach speed for the reasons previously discussed. However, by holding N_β constant for the two tasks it can be shown[9] that the heading response of the simulated aircraft to rudder input was unchanged as a result of the change in approach speed. In addition, the response of the simulated aircraft to lateral turbulence was kept the same for both approach speeds by retaining identical values of N_v. The rolling response of the aircraft was affected somewhat by the change in forward speed, but this effect is felt to be insignificant since the lateral and pitch characteristics used in the visual task were changed to provide reasonable performance in these channels for the instrument approach task.

2.3 Results

The results of this investigation are presented as contours of constant pilot opinion separating the regions of normal operation and emergency operation ($3\frac{1}{2}$ boundaries), and the regions of emergency operation and no operation ($6\frac{1}{2}$ boundaries), on directional damping-control sensitivity planes. Figure 8 presents the handling qualities boundaries for the instrument approach task determined for the lowest value of N_β tested, $N_\beta = 0.5$, and indicates a typical pattern of points tested to determine the directional handling qualities boundaries. Similar details for $N_\beta = 1.0$ and 1.75 are given in Ref. 9. The pilot ratings shown are averages of the evaluations of at least two pilots and are presented to indicate the gradients determined across the planes. The $3\frac{1}{2}$ boundary is shown as a shaded area to indicate that this boundary cannot be determined with a high degree of accuracy and to emphasize that the boundary represents a transition from the normal operation region to the emergency operation region. The $6\frac{1}{2}$ boundary, on the other hand, was well defined for all three values of N_β tested, and for this reason is shown as a solid line in Fig. 8.

Since the purpose of this investigaion was to determine the effect on the directional handling qualities boundaries of the task performed, the results of Ref. 2, using the visual approach task, are presented in Fig. 9 for the three values of N_β tested, 0.5, 1.0, and 1.75, along with the corresponding results from this investigation using an instrument approach task.

The results for the instrument approach task show the same general trends as determined in the visual task, namely, that increasing the weathercock stability in the presence of turbulence requires significantly larger values of damping and control sensitivity to maintain a given level of directional handling qualities as indicated by pilot opinion. For the instrument approach task, the $6\frac{1}{2}$ and $3\frac{1}{2}$ boundaries for both $N_\beta = 0.5$ and 1.0 show significant increases in the minimum damping levels required and a change in shape, whereas the

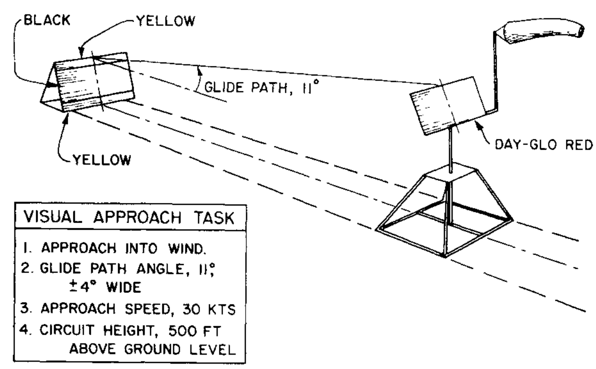

Fig. 7 Visual approach task showing glide path indicator.

boundaries are essentially unchanged for $N_\beta = 1.75$. The left-hand portions of both the $3\frac{1}{2}$ and $6\frac{1}{2}$ boundaries for a given N_β were essentially unaltered by the change of task, a result also determined in Ref. 12 for evaluations made during hovering maneuvers and visual approaches.

2.4 Discussion

In an attempt to understand the changes in the handling qualities boundaries shown for the two tasks performed, use of the theoretical approach to the definition of these handling qualities boundaries suggested in Ref. 12 is made. Briefly, this analysis assumes a pilot-aircraft system and a relatively simple pilot describing function (Fig. 10). This approach indicates that a pilot, when assessing an aircraft's handling qualities, takes into account the characteristics of 1) the control inputs and aircraft responses to bring about desired maneuvers, 2) the aircraft's response to atmospheric turbulence, and 3) the control inputs required to suppress this undesired response.

In low-speed, low-altitude tasks, such as used here, the last two of these characteristics appear to impose the more stringent requirements on the design than those necessary to provide adequate control and response for maneuvering in the absence of turbulence. It is assumed that the pilot reacts to minimize the difference between the response he desires and the actual response of the aircraft. He therefore forms part of the closed loop shown in Fig. 10 and performs a "compensatory" task.[13]

Utilization of the specifications of the closed-loop performance contained in Ref. 12 (adjustment of pilot's gain as a function of $N_{\delta r}$, N_r, N_β and pilot's lead time constant a to maintain a constant phase margin of 45°) yielded surprisingly good correlations between theoretically predicted and experimentally determined $3\frac{1}{2}$ and $6\frac{1}{2}$ boundaries. This theoretical approach combines the effects of turbulence and the aircraft's dynamic characteristics into three apparently meaningful parameters that are used to determine various parts of the boundaries. These include:

1) A constant value of rms rudder control input σ_δ, defining the left-hand, low-control sensitivity portion of the boundaries.

2) A constant value of rms heading response σ_ψ, defining the minimum damping level.

3) A constant value of the ratio of pilot gain to weathercock stability K_p/N_β, defining the right-hand portion. For a given N_β, this part of the $3\frac{1}{2}$ boundary is determined by the minimum gain that the pilot wants to use, whereas the similar part of the $6\frac{1}{2}$ boundary results from the minimum gain that he is able to use, and further movement to the right in the control sensitivity-damping plane leads to unstable loop closure reflected by so-called pilot-induced oscillation.

An example of how these criteria form a typical boundary is shown in Fig. 11, which also includes typical pilot comments on the flight characteristics occurring in the regions outside the boundary. Appropriate alterations in the levels of these parameters from visual to instrument flying allowed reasonable fitting of the handling qualities boundaries for each condition tested. These changes are discussed in detail in Ref. 9 and indicate that the pilot insists on much more stringent re-

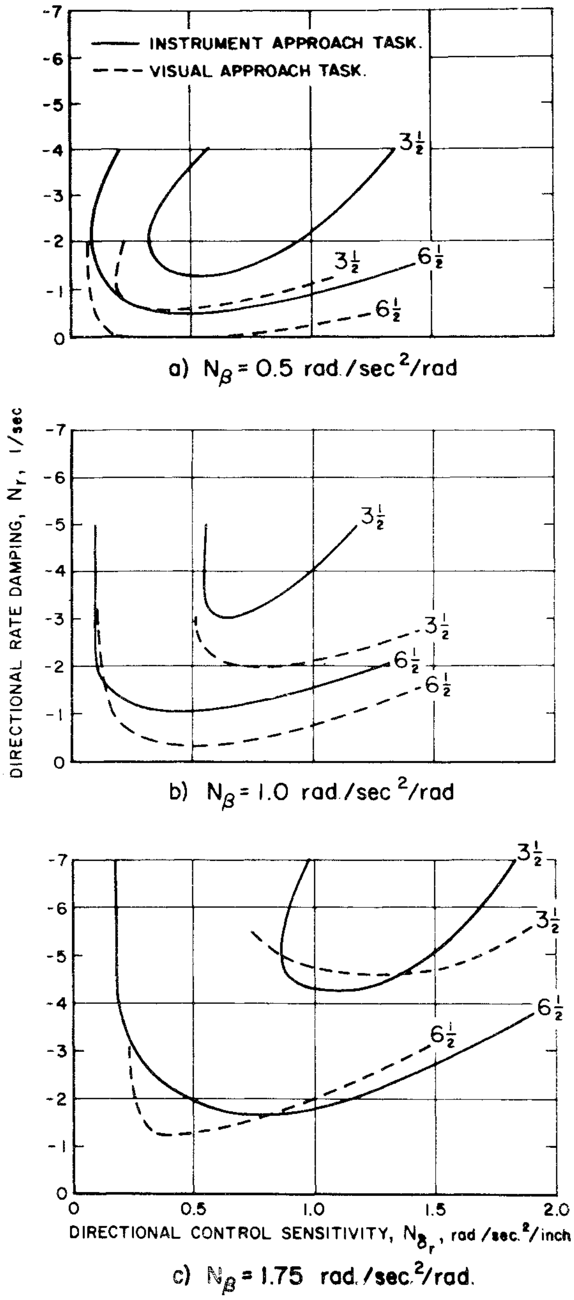

Fig. 9 Comparison of handling qualities boundaries for visual and instrument approach tasks.

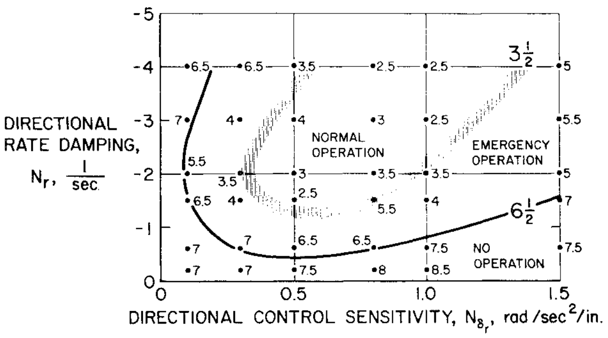

Fig. 8 Handling qualities boundaries, instrument approach task, $N_\beta = 0.5\ \frac{\text{rad/sec}^2}{\text{rad}}$.

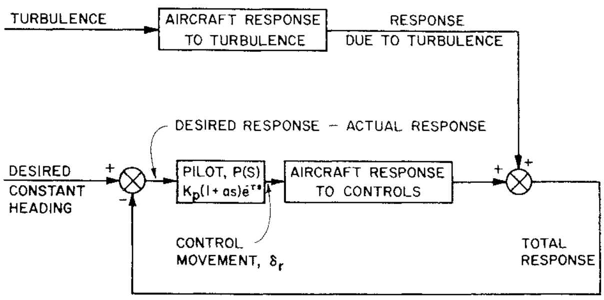

Fig. 10 Pilot-aircraft system for flight in turbulence.

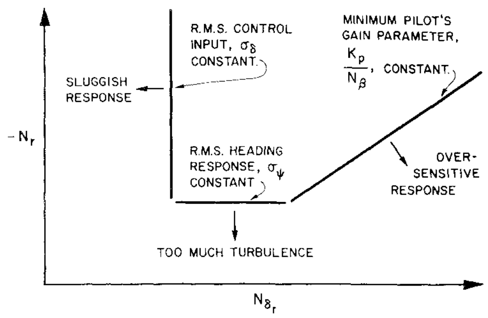

Fig. 11 Theoretical parameters used to define handling qualities boundaries (Ref. 12).

quirements during instrument flying, hence, allowing less deviation from his desired flight conditions.

A similar investigation[14] showed that, for a given set of directional characteristics, better pilot ratings were obtained during an instrument approach task than during a visual approach task. These results are opposite to the trends shown in this investigation. The fact that controlled turbulence was not included in the tests of Ref. 14 probably rules out any direct comparison with this investigation where the requirements *to control the response of the aircraft to turbulence* apparently overshadowed any requirements based on open-loop criteria, such as directional damping ratio or period of oscillation. In addition, the instrument approach task used was not carried to the same approach limits as used in this investigation.

In support of these statements, an observation from a low-speed investigation of longitudinal characteristics[15] indicated "the pilots felt that the dynamics were 'masked' by the strong angular damping and extreme concentration required of the pilot just to perform the difficult instrument approach task" and "the 'tightness' of the pilot-control loop tended to conceal the lower frequency characteristics."

2.5 Conclusions

This comparison of V/STOL directional handling qualities requirements for a visual and an instrument approach task using an airborne simulator yielded the following conclusions:

1) An instrument approach task requires more stringent directional handling qualities than an equivalent visual approach task.

2) Increasing the weathercock stability in the presence of turbulence required significantly larger values of damping, confirming the trend found in a similar investigation using a visual task. These large damping levels were required primarily to reduce the effects of turbulence; and, hence, the inclusion of a controlled, simulated turbulence was extremely important to a realistic simulation.

3) Theoretical predictions from a pilot-aircraft synthesis were found to give encouraging correlation with pilot-opinion assessments of the directional control and response requirements for an instrument approach task in simulated turbulence. This theoretical approach also provided a plausible explanation for the effect of directional handling qualities requirements of the task performed by the pilot.

3. Simulation of a Propeller-Driven Tilt-Wing V/STOL Aircraft

As was mentioned in the Introduction, a simulation of a tilt-wing V/STOL aircraft, the Canadair CL-84, was undertaken principally to determine the influence on the handling qualities of 1) backlash and flexibility in various locations in the control systems and 2) various realistic stability augmentation failures in the presence of these backlashes during a visual hovering task. It can be appreciated that the control systems of this type of tilt-wing aircraft requiring complex mixing of control inputs as a function of wing angle are very susceptible to flexibility and backlash problems.

The first portion of the program was concerned with variations in vertical characteristics while keeping the rotational degrees of freedom simple but representative of the fully stabilized aircraft. The second part investigated the effects of various levels of flexibility, represented by first-order time lags, and backlash in the roll and pitch-control systems and the influence of a variety of Stability Augmentation System (SAS) failures on the pilot's ability to control the aircraft in the presence of these control system characteristics. All SAS channels were simulated realistically including the limits of authority and could be failed one channel at a time or in any desired combination.

The pilot's height control was changed from the helicopter collective type of Fig. 3 to a throttle type, hence duplicating the location and sense of the flight controls of the actual aircraft. A simulated wind of 15 knots was included in the equations of motion to produce realistic effects of turning out of wind. Turbulence, however, was not included in this simulation.

3.1 Test Procedures

The maneuvers and evaluation procedures outlined below were used throughout the investigations subsequently described. After the programed test conditions had been set up by the safety pilot, without the evaluation pilot's knowledge of what the particular settings were, the safety pilot lifted the helicopter into the hover about 5 ft above the ground, the autopilot was engaged, the analog computer switched to its "operate" mode, and the evaluation pilot took complete control of all six degrees of freedom.

He then executed a series of low-speed maneuvers that included steady hovering, increasing and decreasing altitude vertically, longitudinal translations up to approximately 15 knots, lateral translations, turns over a spot, and finally an attempt at landing the simulator.

Two ratings were assigned by the pilot to each model, based on its characteristics during the gross manuevers and during the much more precise landing phase. This latter part of the task proved to be the more demanding, particularly in the evaluation of the vertical characteristics, and almost invariably received a higher rating. Each data point presented is an average of the evaluations of at least two pilots.

3.2 Simulation of the Vertical or Height Control

Two sources of lost motion or backlash were determined in the vertical thrust control system of the CL-84 during ground tests. The first was between the pilot's power control and the engine power lever (B_1, degrees of engine power lever) simulated by a mechanical device on the throttle lever; and the second was in the actual positioning of the angle of the main

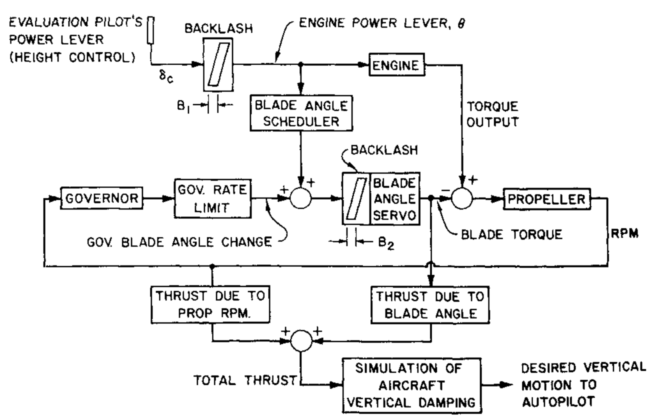

Fig. 12 CL-84 hovering thrust circuit.

rotor blades (B_2, degrees of blade angle) simulated by an electrical analog backlash circuit.

The equation describing the motion in the vertical degree of freedom, or the model for this part of the simulation was

$$\dot{w}(\text{vertical acceleration}) = [(1/m)(\partial T/\partial \delta_c)]\delta_c + Z_w \cdot w \quad (2)$$

The variation of thrust with pilot's power lever input $\partial T/\partial \delta_c$ included the dynamics of the engine, the propeller, the blade angle servo, and the governor as well as the two backlash terms as shown in Fig. 12.

A few preliminary tests established that a thrust margin of 10% (i.e., $T/W = 1.10$) was adequate in the presence of the level vertical damping ($Z_W = -0.16$ ft/sec^2/fps) predicted for the aircraft and was used throughout. Reference 16 confirms this result.

The power lever backlash resulted in a region of lost motion at the pilot's control (1 in. of pilot's lever movement = 9.71° of engine power lever). Propeller backlash, however, besides contributing to the total lost motion, had a further disquieting influence on the control of the aircraft in that because of its position in the closed loop of the governor system, it resulted in a fluctuating thrust output that caused vertical movement of the aircraft independent of pilot input. The period and amplitude of this disturbance were functions of the magnitude of the backlash, both increasing with increasing backlash. The thrust variations in the model for $B_2 = 0.25°$ are shown in Fig. 13 along with the thrust response to a step input.

3.2.1 *Results*

Figure 14 shows the backlash combinations tested and indicates that, for satisfatory operation throughout all the flight maneuvers previously described, the lost motion between the pilot's height control and the engine power lever must be less than 2° (approximately 0.2 in. of pilot's control), and the blade angle backlash must be less than 0.3°.

3.3 Stability Augmentation System (SAS) Failures with Various Levels of Roll and Pitch Control Backlash and Flexibility

The stability augmentation system of the CL-84 includes angular rate damping about all three rotational axes, an attitude or stiffness term in pitch, and a lag rate damping term in roll, all of which, it is anticipated, will be used in normal operation. The authority of these systems is limited and the simulation took account of these limitations.

During ground tests of the actual aircraft, backlash and flexibility were found in the systems positioning the differential blade angle used for roll control in the hover and in the tail rotor used for low-speed pitch control. Initially these nonlinear effects were intepreted and programed as backlash only, but as a clearer understanding of their characteristics was achieved, combinations of first-order time lags, representing flexibility, and backlash were employed in the simulation.

The flight maneuvers used during the evaluations were the same as those described in the section dealing with test procedures. The fully stabilized aircraft was flown at the beginning of each test point and the safety pilot failed the appropriate SAS channel, without warning the evaluation pilot, during a test maneuver. This presented him with realistically severe conditions to cope with while flying the new characteristics.

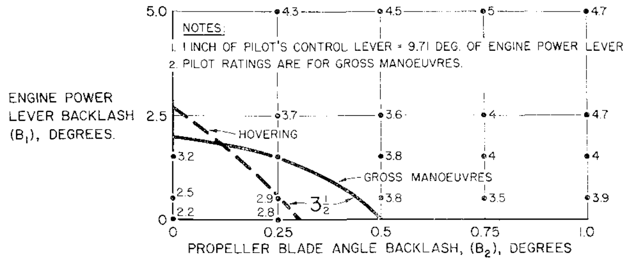

Fig. 14 Pilots' evaluation of backlash in height control system.

3.3.1 *Equations of motion*

Although the simulator could not reproduce the motions associated with the longitudinal and lateral translational degrees of freedom, the equations describing these motions for the CL-84 were programed on the analog computer so that the rotational modes of motion were correctly influenced by the translational characteristics.

The equations of motion are not presented in detail here. See Ref. 6 for this information. A simplified flow diagram of the longitudinal equations, representing part of the model of the CL-84, is presented in Fig. 15 in which it can be seen that both the inherent characteristics of the CL-84 aircraft and the additions due to the stability augmentation system were simulated. Hence, for example, when the pitch angular damping contribution from the SAS was failed, the pilot was left with flying characteristics appropriate to the aircraft with this channel inoperative. The backlash and flexibility terms were situated in the simulation to influence all inputs derived from the aircraft's control system, but did not affect the inherent aircraft characteristics.

3.3.2 *Results*

Various combinations of backlash in the roll, pitch, and height control systems were tested and toward the end of the program first-order time lags were included in all three modes to provide a more realistic representation of the control system flexibility determined experimentally on the actual aircraft. The versatility of this "model-controlled" method of simulation was especially valuable in that within a few hours of establishing new conditions, following improvements on the aircraft control systems, the characteristics were programed on the analog computer and were test flown immediately.

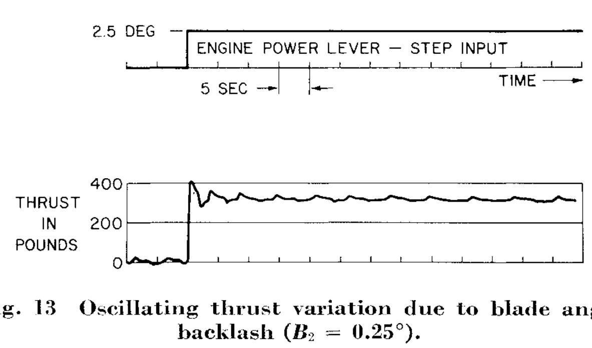

Fig. 13 Oscillating thrust variation due to blade angle backlash ($B_2 = 0.25°$).

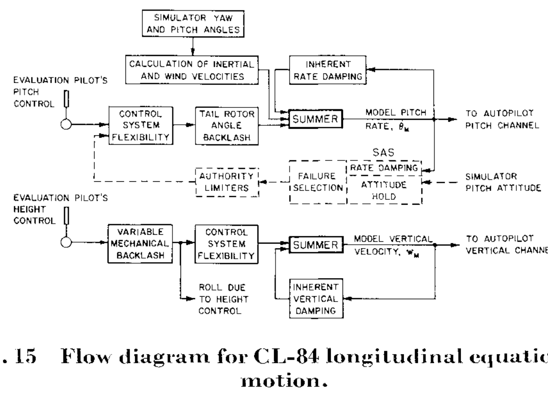

Fig. 15 Flow diagram for CL-84 longitudinal equations of motion.

Table 1 Stability augmentation failure results, pilot opinion results.

CONTROL PARAMETER						SAS CHANNEL FAILED															
PITCH		ROLL		HEIGHT CONTROL		NONE, i.e. FULLY STABILIZED A/C		ALL FAILED SIMULTANEOUSLY		PITCH DAMPING		ROLL DAMPING		PITCH STIFFNESS		PITCH DAMPING AND STIFFNESS		PITCH DAMPING WITHOUT STIFFNESS INITIALLY		YAW DAMPING	
BACKLASH, BLADE ANGLE, DEG.	FIRST ORDER TIME CONSTANT, SEC.	BACKLASH, BLADE ANGLE, DEG.	FIRST ORDER TIME CONSTANT, SEC.	BACKLASH, AT PILOT'S HAND, IN.	FIRST ORDER TIME CONSTANT, SEC.	G	L	G	L	G	L	G	L	G	L	G	L	G	L	G	L
0		0		0.05		2.1	1.9	5	4.8	5.2	4.1	4.6	3.6	2.5	2.2	4.8	3.5	5	3.2	3	2.6
0		0		0.10						5	5										
0	HELD ZERO FOR THESE TESTS	0	HELD ZERO FOR THESE TESTS	0.26						4	4										
0		0		0.51						4.8	4.9			4.5	4.5						
0.5		1.0		0.10		4.2	4.5	7.5	7.5	5.8	5.8	5.8	6								
0.9		0.5		0.26		3.6	3.6	6.8	6.8	5.2	5.2	4.6	4.6								
0.9		1.5		0.26		4.1	4.1	7.5	7.5												
0.9		2.0		0.26		5	4.8	8.2	8.2												
1.9		0.5		0.51		4	4	7.2	7.2												
1.8		1.0		0.51		4.5	4.8	7.8	8.2	6.5	6.5	6	6.2	4.6	5						
1.9		1.9		0.51		5.2	5.5	8	8												
0.6	0.10	0.25	0.03	0.2	0.05	2.6	2.6	6.0	5.1	5.2	5	4.5	4.8								
0.6	0.15	0.25	0.20	0.2	0.05	3.5	3.4	6.5	6.8	6.5	7.2	6.5	6.0								

G = RATING IN GROSS MANOEUVRES.
L = RATING IN LANDING.

Table 1 shows the combinations tested along with the averaged results arrived at from the ratings given by at least two pilots. It became evident from a few preliminary flights that the pilots experienced the greatest difficulty when all channels were failed and somewhat less difficulty when the pitch damping and roll damping were individually removed. Other failures were relatively easy to cope with. For these reasons SAS failures involving all channels were thoroughly investigated whereas some of the single channel failures were tested with only a limited number of control conditions.

The experiment was designed essentially to establish what control system characteristics must be provided to achieve a pilot rating of $3\frac{1}{2}$ or better for the fully stabilized aircraft and $6\frac{1}{2}$ or better following any failure in the SAS. No doubt there were many combinations that would have fulfilled these conditions, but only a few were meaningful from a practical viewpoint. Table 1 indicates that these requirements were achieved only twice during the experiments and occurred with 1) backlash of 0.05 in. in the height control and no backlash in either roll or pitch and 2) with the conditions noted in the twelfth line of Table 1. These latter conditions appeared to be representative of what could be achieved on the actual aircraft and concluded the testing with the airborne simulator.

3.4 Conclusions

The following conclusions are drawn from this investigation:

1) The change in the height-control lever from a helicopter collective-type, to which the pilots were accustomed, to a throttle type, presented no difficulties after the first trip.

2) For satisfactory flight operation, the backlash in the height-control lever should be less than 0.2 in. at the pilot's hand (2° of throttle lever movement), and the free play in the positioning of the main propeller blades should be less than approximately 0.3°. The former result was found during both the investigation concerned solely with the height-control characteristics and also during the SAS failure tests.

3) These same propellers supply the differential thrust necessary for roll control at low speeds. The backlash requirement for satisfactory control with all stability augmentation channels engaged was essentially the same as that determined for the collective control, being approximately 0.25° when the first-order time lag of the control system was small. The free play in the positioning of the tail rotor propellers used for pitch control at low airspeeds had to be less than approximately 0.6° with a small lag time.

4) It is felt that the testing performed in this simulator, where three company pilots were exposed to a great variety of flying characteristics, was invaluable in preparing them for subsequent flight in the actual aircraft. In addition, comments by the pilots following initial flights of the CL-84 indicated that a high level of fidelity existed in the simulation.

Conclusions

It is seen from the two programs outlined in this paper that the model-controlled method of flight simulation provides the versatility necessary to undertake programs of a general research nature as well as simulation of particular aircraft. The ease with which a wide variety of parameters can be altered compares favorably with fixed-base simulators and its inherent ability to "wash out" the characteristics of the vehicle used as the simulator is immensely useful.

The investigation of directional handling qualities indicated that requirements for instrument flying are more stringent than for visual flight and assessed the magnitude of the changes necessary in several important stability derivatives to maintain desirable and minimal flying characteristics. A simulation of a tilt-wing V/STOL aircraft indicated the detrimental influence of backlash and flexibility in its flight control systems and the allowable limits of these effects for various flight conditions.

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