Investigation of the Application of Direct Translational Control to VTOL Aircraft

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The possibility of employing a mixed translation and attitude control system through a single cockpit stick has been investigated for low-speed flight control of VTOL aircraft. In this way it would be possible to command more directly low-speed longitudinal and lateral translations and to reduce the amount of installed thrust required for attitude control of VTOL aircraft. The maneuvering translation concept is not to be confused in the longitudinal plane with the more gross thrust vectoring requirement necessary for transition to wing-borne flight. In the current study, combined control schemes were evaluated on the longitudinal axis of a simulated VTOL aircraft during performance of a multiaxis IFR (instrument flight rules) hover task. With pilot opinion as a measure, some combinations of attitude and translational controls were found to be more satisfactory than attitude controls alone. Systems receiving the best ratings were 1) fully stabilized airframe provided with direct translation acceleration control and 2) stick steering control of attitude with open-loop shaping of the translational control to give pseudo-velocity control. Acceptable translational controls seem particularly well suited to IFR hover tasks, since they allow control movements to be minimized. There were definite indications that the larger control movements associated with VFR (visual flight rules) flight, where the pilot is less inhibited by the instrument scanning process, would result in mismatching of the attitude and translation controls.

Nomenclature

δ_{stick} = control stick displacement, in.
δ_{control} = output of shaping network, in.
ϵ = error signal to pilot
ζ_M = damping ratio of attitude shaping network
ζ_x = damping ratio of translational shaping network
K_C = shaping network gain, in./in.
K_θ = pilot gain in response to attitude error, in./rad
K_x = pilot gain in response to displacement error, in./ft
M_δ = pitching moment per inch of stick deflection
M_q = rate of change of pitching moment with pitch rate, sec^{-1}
M_u = rate of change of pitching moment with longitudinal velocity, rad/ft/sec
q = pitch rate (body axis)
S = Laplace operator
τ = pilot lag, sec
T_L = pilot lead time constant, sec
T_N = pilot neuromuscular lag time constant, sec
T_I = pilot lag time constant, sec
θ = Euler angle for pitch, rad
u = velocity along x body axis, fps
X = longitudinal displacement (body axis), ft
X_δ = longitudinal force due to pusher, ft/sec²/in.
X_u = rate of change of longitudinal force with velocity, sec^{-1}
X_θ = rate of change of longitudinal force with pitch angle, ft/sec²/rad
Y = polynomial of form $\dfrac{(a_{n-1}S^{n-1} + a_{n-2}S^{n-2} + \ldots a)}{(b_nS^n + b_{n-1}S^{n-1} + \ldots b)}$
Y_A = airframe transfer function
Y_p = pilot transfer function
Y_C = shaping network transfer function
Y_{OL} = system open-loop transfer function
ω_M = natural frequency of attitude shaping network
ω_X = natural frequency of translation shaping network
Z_M = attitude shaping network zero
Z_X = translation shaping network zero

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Introduction

PROVISION of control power at low speeds in current and projected V/STOL vehicles is recognized as a major design problem that interacts with the engine-airfame choice by requiring increased engine size and weight to provide a given controlled lifting capability.

The problem is often aggravated by the inefficient use of engine mass flow by bleeding to provide control of vehicle position through attitude change. Although it is a fact that a certain amount of attitude control is required (depending on the vehicle configuration and disk loading) to counteract disturbing moments arising from velocity changes, a large amount of the attitude control is used indirectly to provide position control. If this position control could be provided directly through a translational controller, a reduction in attitude control power requirements would undoubtedly accrue. Furthermore, this translational control could be provided by thrust vectoring (Fig. 1), circumventing the losses associated with bleeding the power sources.

With this type of control system, it is possible to command attitude and translation through the same controller. It is worth noting that such a control type is available on many helicopters through the flexible mechanical coupling between the rotor and the helicopter fuselage.

A simplified pilot-airframe analysis was made to investigate the more basic aspects of the performance of a system employing a mixed control. The prime objective was to eliminate the combinations of attitude and translation control which the pilot could not hope to use successfully, e.g., attitude acceleration control in combination with translational acceleration control. In this way it was possible to reduce the size of the subsequent simulator test program and gain a useful insight into the mechanics of the system.

It was decided to restrict the test program to an investigation of the performance of the system under IFR conditions. Prior work had indicated that a pilot normally utilizes much larger attitude displacements under VFR conditions than under IFR conditions in positioning a V/STOL vehicle. This is possibly attributable to the fact that current IFR display schemes still require discrete flight status sampling on the part

Table 1 Types of control systems

Type of control	Description of control
Rate control of attitude	1) Steady-state rate response of the airframe to a step command at the stick by feedback of an attitude rate signal. 2) Steady-state rate response of the airframe to a step command at the stick by placement of a shaping network in the input side of the control system.
Attitude (or stick) steering	1) Steady-state attitude displacement of the airframe in response to a step command at the stick by feedback of attitude and rate signals. 2) Steady-state attitude displacement of the airframe in response to a step command at the stick by placement of a shaping network in the input side of the control system.
Stabilized platform	1) An airframe constrained by displacement and rate feedback in such a manner that the attitude remains zero at all times.
Velocity pusher	An open-loop shaping network in the translation control system causes the airframe to respond with steady translational velocity to a step stick input.
Acceleration pusher	A control system such that the airframe responds to a step stick input with a steady acceleration output.

of the pilot and, hence, a reluctance to cause large changes during this scan period. Large attitude displacements typical of VFR flying were found during the current program to cause mismatching of the attitude and translation control, leading to the tentative conclusion that a mixed control would find its best application in IFR tasks. A VFR simulator program will be needed to clarify this point.

A further restriction was imposed on the tests, in that only the hover mode was investigated. In this way it was possible to limit the number of variables and retain a clear understanding of the mechanics of the system. Future work, when IFR transition techniques are developed, will include tests of the mixed controller during transition.

A broad range of vehicle characteristics was evaluated. This was accomplished by varying the parameters M_u and X_u from the low values associated with jet lift vehicles to the high values associated with propellered vehicles. Gusts and steady winds were also simulated to add realism to the flying task.

Three pilots were employed in evaluating the handling qualities of the system, with experience ranging from high-performance U. S. Air Force fighters to low-performance commercial airplanes and helicopters. All had some previous experience of V/STOL simulator flying. The Cooper pilot rating scale was used exclusively to measure the acceptability of a particular system.

Simplified Pilot Airframe Analysis

The following analysis applies strictly to an IFR compensatory tracking task because of the nature of the pilot describing function used. The hovering task employed in the experimental program approximates closely such a task. As hovering involves precise control of the longitudinal displacement x, it would seem that the pilot's ability to control a hovering vehicle would be enhanced if he were given control of x directly rather than control of x through attitude. This can be shown to be so under ideal conditions where no extraneous disturbances are applied to the airframe.

Consider the simple case of a "linear" pilot responding to displacement information only

$$Y_p = \frac{\delta_{\text{stick}}}{\epsilon} = \frac{K_x \cdot e^{-\tau s} \cdot (T_L S + 1)}{(T_I S + 1)(T_N S + 1)}$$

where Y_p is the pilot describing function and attempting to maintain a fixed position in the x direction in an airframe with the transfer functions

$$Y_A(x) = \frac{x}{\delta_{\text{control}}} = \frac{(S^2 - M_q S)X_\delta + X_\theta M_\delta}{S[S^3 - (X_u + M_q)S^2 + X_u M_q S - X_\theta M_u]}$$

and

$$Y_A(\theta) = \frac{\theta}{\delta_{\text{control}}} = \frac{(S - X_u)M_\delta + X_\delta M_u}{S^3 - (X_u + M_q)S^2 + X_u M_q S - X_\theta M_u}$$

If the control system is such that forward loop shaping of the pilot's command can occur, it is possible to have a pseudo-velocity controller or velocity pusher (Table 1)[1-3]:

$$Y_c = \frac{\delta_{\text{control}}}{\delta_{\text{stick}}} = \frac{S(S + Z)}{S^2 + 2\zeta\omega S + \omega^2}$$

Combining these into the closed-loop system of a pilot flying a compensatory tracking (of x) task as shown in Fig. 2, it is possible to draw some broad conclusions regarding the more important parameters involved.

To make possible the presentation of results in the root locus form, an approximation of $e^{-\gamma s}$ in the pilot transfer function is introduced; hence,

$$Y_p = \frac{K_x(T_L S + 1)[-(\tau/2)S + 1]}{(T_I S + 1)(T_N S + 1)[(\tau/2)S + 1]}$$

and if the lag terms T_I, T_N, and τ are lumped into an equivalent time constant that has the value 0.2, the pilot transfer function becomes

$$Y_p = \frac{K_x(T_L S + 1)(-\cdot 1S + 1)}{(\cdot 1S + 1)}$$

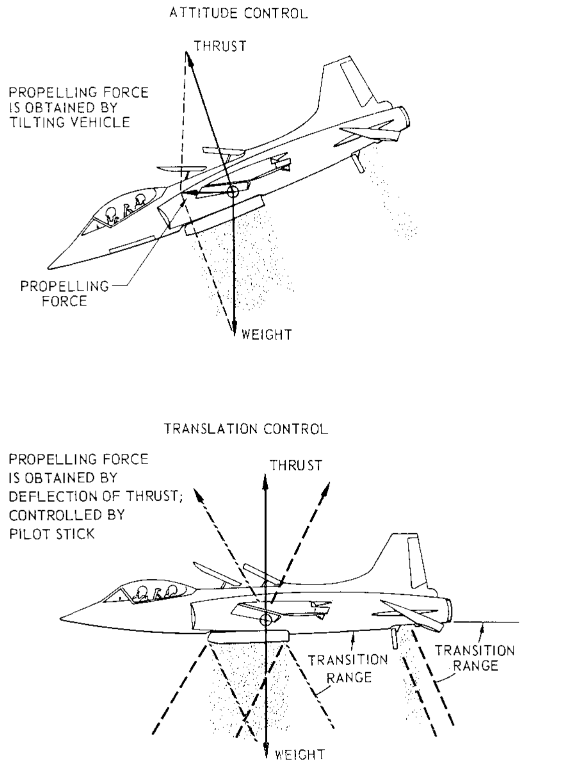

Fig. 1 Application of attitude and translation controls to a VTOL aircraft.

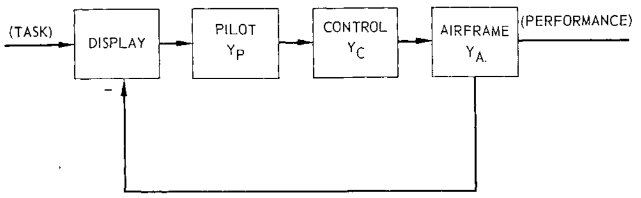

Fig. 2 Block diagram of compensatory tracking task.

It should be remembered that such an approximation will normally result in a characteristic equation of the form $1 - Y = 0$, under which circumstances the Nyquist point (neutral closed-loop stability point) will take the value $NP = (1, j, 0)$, and phase margins on the Bode plot should be taken with reference to the 0° line. We now study the stability of the pilot-airframe system as the mode of control and type of information available to the pilot changes. When the characteristic equation is $1 + Y_{OL} = 0$ and the pilot flies his task without generating any lead T_L, the characteristic equation becomes

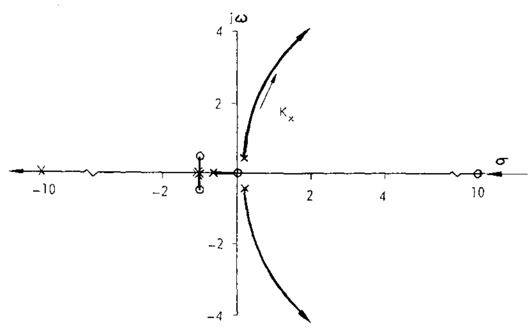

Fig. 4 Pilot controlling displacement through attitude and translational acceleration control.

Other system variables, not noted previously, can influence the pilot's ability to stabilize the system of which he is a part. Lead is probably the most important of these, and it is heavily dependent on the type of display used and the force characteristics of the stick. The mathematics of incorporating these influences into the analysis are cumbersome and do little to improve the basic understanding of the stability of the system. A more interesting point is to consider the stability of the system when an automatic control restrains the attitude to some datum and allows the pilot to fly displacement only. In this situation, the airframe transfer function is $Y_A = X_\delta/[S(S - X_u)]$, and if the pilot has direct control of displacement through a shaping network of the form $Y_C = K_C S/(S - C)$, the root-locus plot of Fig. 7 shows that the pilot can stabilize the system over a limited range of total system gain.

$$1 = \frac{K_x(S - 10)(\{[X_\theta M_\delta S(S + Z_M)]/(S^2 + 2\zeta_M\omega_M S + \omega_M{}^2)\} + (S^2 - M_q S)\{[X_\delta S(S + Z_x)]/(S^2 + 2\zeta_x\omega_x S + \omega_x{}^2)\})}{S(S + 10)[S^3 - (X_u + M_q)S^2 + X_u M_q S - X_\theta M_u]}$$

For closed-loop stability, it is necessary that the locus of solutions of this equation as the gain K_x is varied should remain in the left half of the complex plane shown in Fig. 3. If the pilot attempts to control position using attitude, he becomes part of an unstable situation even with attitude stick steering, as indicated on Fig. 3, where one branch of the locus always remains in the right half-plane. The provision of translational acceleration control does little to improve the stability of the system, because only the branch of the locus in the left-hand plane is appreciably affected by the introduction of the translation control, as Fig. 4 shows. However, a forward loop shaper (mechanical lead-lag device) inserted in the translational control circuit is capable of providing pseudo-velocity control and makes it possible for the pilot to stabilize the system over a limited range of system gain. This corresponds to the range of gains K_x, where the locus crosses the imaginary axis into the left-hand plane in Fig. 5. A large part of the difficulty in stabilizing the system as simulated by the mathematical models arises from the "model" pilot flying attitude and displacement with information on displacement alone.

Reverting to the mathematics of the situation, if the pilot now displaces the control in response to displacement and attitude cues, the pilot transfer function becomes

$$Y_p = K_x[1 + (K_\theta/K_x)\cdot(\theta/x)]e^{-\tau s}$$

and Fig. 6 shows how an attitude rate damped system performs under these conditions; the pilot is now capable of stabilizing the system for all values of gain.

Furthermore, if we look at the Bode plot, Fig. 8 of the system, it is possible to arrange the gain such that a phase margin (60°) sufficient for good system performance is obtained.

This simplified analytical treatment has shown that improved tracking performance will occur if the amount of mental work required of the pilot is kept low. For example, where the pilot was given attitude and displacement information, the stability of the system improved over the situation where attitude information alone was presented. Furthermore, where the attitude mode was stabilized automatically, the reduction in mental effort resulted in improved system performance. The use of the shaping (or lead-lag) network in the translation control, providing the pilot direct control of velocity rather than acceleration, was a further example of improved system performance. As a result of this analysis it was tentatively concluded that the following combinations of attitude and translational control should be evaluated on the

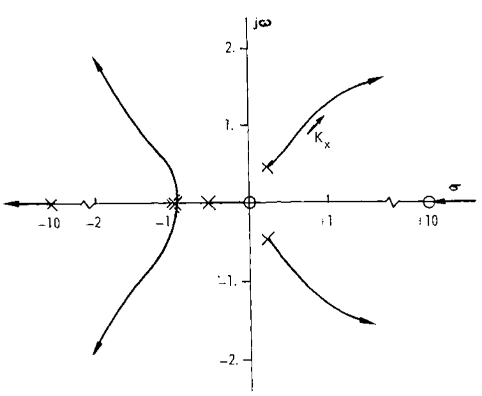

Fig. 3 Pilot controlling displacement through attitude.

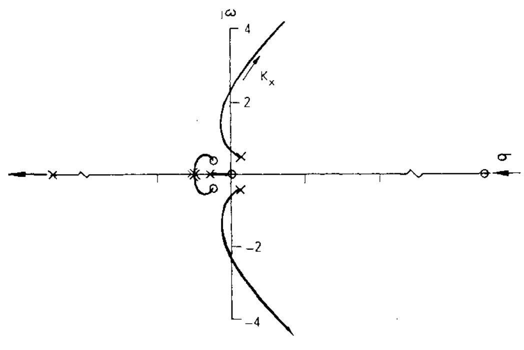

Fig. 5 Pilot controlling displacement with attitude and translational velocity control.

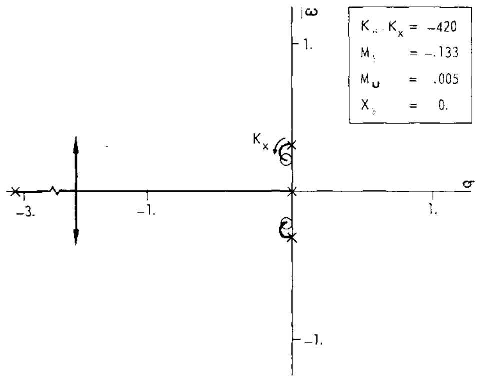

Fig. 6 Pilot having attitude and displacement information.

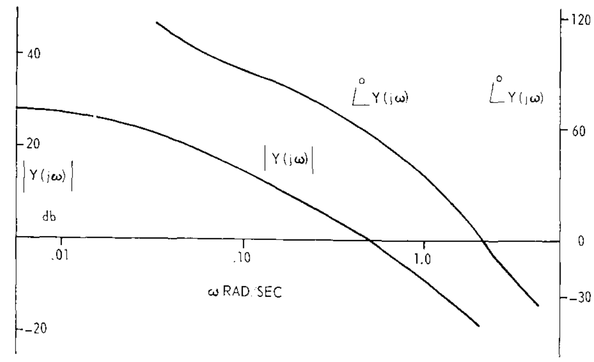

Fig. 8 Pilot controlling displacement of stabilized platform.

simulator: 1) rate control of attitude in combination with control of translational velocity; 2) stick steering control of attitude with translational velocity control; and 3) full attitude stabilization in combination with translational velocity control.

Other more practical considerations, not amenable to a system analysis, have a strong bearing on the system performance. The most important of these were the pitching moment and longitudinal force associated with velocity. It was anticipated that these could cause controlling difficulties, particularly if a velocity control, utilizing stick signal shaping, were used. The test program was therefore extended to cover the foregoing three cases with acceleration translation control, as well as the velocity control.

Experimental Procedure

A cockpit simulator (Fig. 9) and associated analog computer equipment were used to evaluate the effect of various combinations of translational and attitude control modes on hovering performance. The pilot's cockpit control movements were directed to the analog computer, which computed the resulting aircraft motion and caused the cockpit instruments to move in an appropriate fashion. The analog computer was arranged to represent the six degrees of freedom of aircraft motion, but the test controls were applied to the longitudinal axis only. The roll and yaw controls were optimized through the use of pilot rating, which resulted in heavily damped, rate feedback control modes. The flight conditions were representative of a simulated IFR situation, flown under a canvas hood similar to that commonly used in training aircraft. Because the best method of employing the translational control in this IFR environment required minimizing the attitude changes, it was felt that motion cues would not be necessary, and the cockpit was therefore utilized in the fixed base mode of operation.

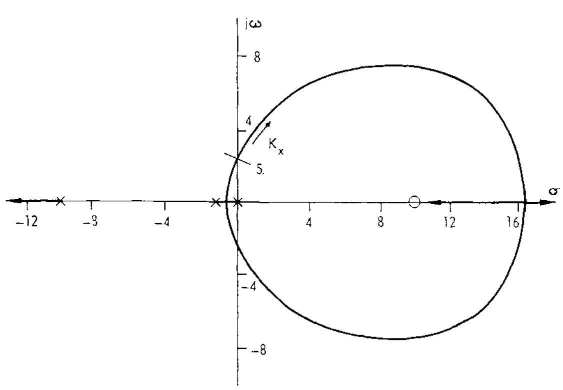

Fig. 7 Pilot controlling displacement of stabilized platform.

The pilot's flight instruments were entirely of the situation display type and function in the so-called "inside-out" manner. Two cathode-ray tubes (CRT) dominated the presentation. The upper-central CRT functioned as a conventional indicator; the lower-central CRT was a plan position indicator. The center of this display represented the aircraft's location, whereas a dot represented the location of the landing pad when it was within 200 ft of the aircraft. The piloting task was oriented about this display. The other instruments comprised conventional displays of altitude, airspeed, rate-of-climb, heading, and thrust vector angle. The lateral stick force gradient was 3 lb/in., and the longitudinal gradient was 3.6 lb/in.

The aircraft simulated was a jet lift VTOL that employed reaction controls on all axes. To make the results as general as possible, the basic airframe longitudinal characteristics were varied. This was accomplished by varying the parameters M_u and X_u. Because of the numerous possible VTOL configurations, X_u and M_u may change independently. Hence, in some tests, X_u was made to correspond to M_u, assuming that the center of action of the force resulting from the lifting source-airframe interference remained fixed. In other tests, X_u was fixed at a level corresponding to a jet-lift system, whereas M_u was varied.

Typical values of M_u are $M_u = 0.005$ (rad/sec²)/fps (jet lift airframe), $M_u = 0.015$ (rad/sec²)/fps (fan-in-wing airframe), and $M_u = 0.043$ (rad/sec²)/fps (propeller airframe). A variety of control modes were tested on the longitudinal axis. A brief description of these modes is given in Table 1.

In all of the tests, attitude and translation were commanded from a common controller (stick). Attitude control was through a feedback control system with no forward loop shaping, whereas translation control employed forward loop

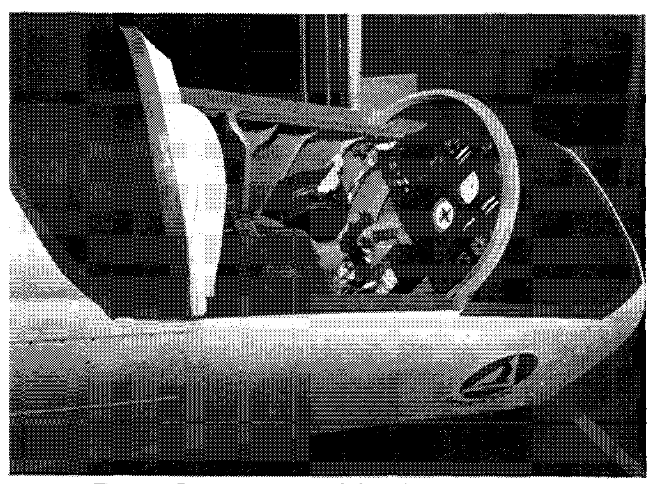

Fig. 9 Two-degrees-of-freedom simulator.

Table 2 Test summary

Test group	Attitude control type	Translational control (pusher) type	M_u	X_u	Wind and gusts	Stick trim
1	Rate feedback	None	−0.005	0	No	Fixed
2	Rate feedback	None	−0.005	−0.016	No	Fixed
3	Stick steering	None	−0.005	0	No	Fixed and moving
4	Stabilized platform	Acceleration	0	−0.016	Yes	Fixed
5	Stabilized platform	Velocity	0	−0.016	No	Fixed
6	Stabilized platform	Velocity	0	0	Yes	Fixed
7	Stabilized platform	Velocity	0	−0.016	Yes	Fixed
8	Stick steering	Acceleration	0	0	Yes	Fixed
9	Stick steering	Acceleration	−0.005	0	Yes	Fixed
10	Stick steering	Velocity	0	0	Yes	Fixed
11	Stick steering	Velocity	−0.005	0	Yes	Fixed
12	Stick steering	Velocity	−0.005	0	Yes	Moving
13	Rate feedback	Velocity	−0.005	0	Yes	Fixed
14	Rate feedback	Velocity	−0.005	−0.016	Yes	Moving

shaping with no feedback. Forward loop shaping was chosen for the translation control because it is anticipated that difficulty will be experienced on an actual aircraft in obtaining a measure of vehicle ground speed to provide the rate feedback needed for an unshaped velocity control. On the other hand, it is quite a simple matter to provide mechanical forward loop shaping.

As previously indicated, lateral and directional control were effected entirely by control of roll and yaw, through rate feedback. Altitude control was by direct throttle command of engine thrust, with a 0.2-sec response lag.

The piloting task used to evaluate the performance of the longitudinal controls involved moving the aircraft forward and laterally to a fixed plan position against a steady wind of 20 knots with superimposed gusts of 4 knots mean deviation, while maintaining altitude and heading at hover. Task priority was established in this order: attaining and maintaining plan position, maintaining altitude, and maintaining heading. The pilot was also allowed the option of inducing large disturbances in attitude and velocity, if such were necessary to evaluate the handling qualities accurately. The test cases flown are listed in Table 2.

Since the task presented to the pilot was entirely IFR in nature, it placed great emphasis on the minimizing of control movements. Generally speaking, the translational controls that were rated highest achieved their ratings because they provided adequate airplane movement with little or no attitude change. In effect, the airplane could be "beeped" about with the stick, whereas attitude, altitude, and heading were held constant.

Three pilots participated in the test program. Their total flying time ranged from less than 1000 to more than 15,000 hr and included experience in sailplanes, helicopters, light aircraft, jet fighters, and large multiengine transport and bomber types. All three of the pilots had varying amounts of actual instrument and previous simulator experience, including IFR hover practice in the simulator used in this investigation. Prior to flying the simulated task, the pilots were given adequate time to adjust to the control situation and settle down to flying representative of their skill level. Control performance was rated using the familiar NASA-Cooper pilot rating system.[4]

Test Results

Basic Airframe Characteristics

Figure 10 shows how pilot rating is affected by variations in M_u in the rate control mode. Previous experience had shown that, when sensitivity of control and rate damping are high, M_u effects are minimized. By choosing M_δ = 0.54 rad/sec²/in. and $M_q = -3.0$ sec^{-1}, it was possible to arrange for the basic airframes to have comparable handling qualities over a large range of M_u.

In the stick steering mode, it was also possible to minimize the effects of M_u (Fig. 11) by proper choice of stick sensitivity

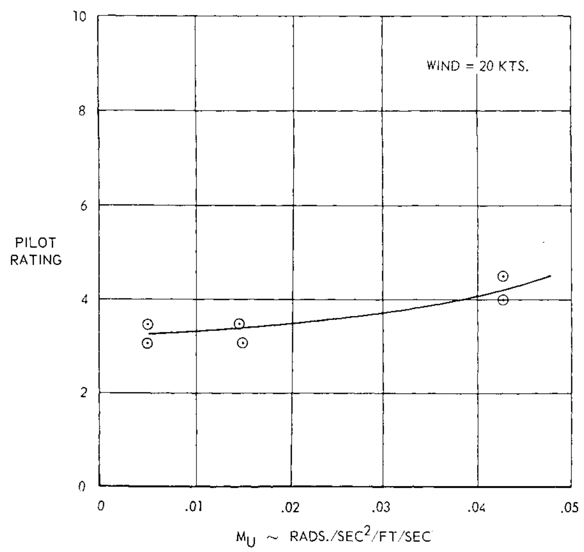

Fig. 10 Basic handling qualities when pilot has rate control of attitude.

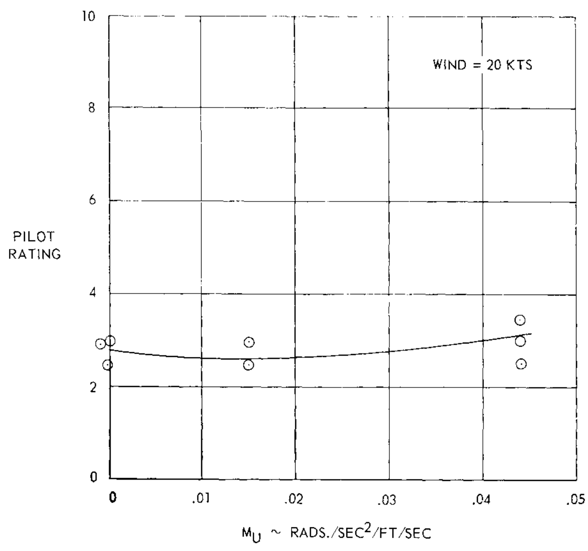

Fig. 11 Basic handling qualities when pilot has stick steering control.

and feedback characteristics. Within the experimental scatter, the pilots showed no preference for a stick that moved with trim demand over one that remained fixed. Figure 11 contains data points for both types of stick.

Airframe with Translational and Attitude Control

Three types of attitude control were investigated in conjunction with the translational controller. These were attitude rate control, attitude stick steering, and fully autostabilized attitude control or the so-called stabilized platform. With the exception of the latter case, the tests were conducted with the pitch trimmer, activated by a button on top of the stick grip. The button would, by selection, either move the stick with trim demand (series trim) or cause the stick to remain fixed during trim (parallel trim). As the test results below show, trim type had no appreciable effect on pilot rating. The stabilized platform had no requirement for a manual trimming system.

Rate Damped Attitude Control

Figures 12 and 13 show the results for the airplane with rate damped control over attitude and velocity control over translation. This type of translation control, where the steady-state response to stick displacement is velocity and not acceleration, is referred to as a velocity pusher (Table 1). It is apparent from Figs. 12 and 13 that there is no advantage in using the translational control or pusher on rate-damped airplanes, as no substantial improvement in pilot rating accrues. In fact, as M_u and X_u increase, the pilots dislike the airframe with the mixed control. The reason for this is that, in attempting to translate to the landing pad in the presence of headwinds, there is a mismatching of the stick displacement required to produce translation against X_u and the stick displacement to overcome pitching moments due to translation. Furthermore, since the X_u effect causes a deceleration force on the airplane due to velocity and the velocity shaping control only provides control of velocity, the airframe cannot be moved against a steady decelerating force. As M_u and X_u increase, the mismatching causes more and more difficulty, as the pilot ratings show. It was hoped that the provision of an attitude trim button that did not cause the stick to move would improve the situation. Comparison of the pilot ratings for a trim device that moved the stick with trim (Fig. 12) and one in which the stick remained fixed (Fig. 13) indicated no particular improvement.

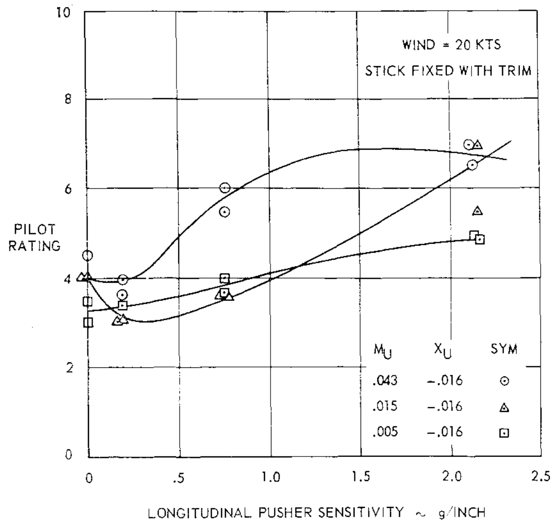

Fig. 13 Velocity pusher on attitude rate damped airframe.

Attitude Stick Steering Control

Attitude stick steering control was introduced to reduce stick activity during the hovering maneuver. It was expected that this would eliminate the unwanted velocity excursions that produce unsatisfactory coupling of attitude and translation.

In the stick steering mode, Fig. 14 shows how an acceleration pusher does little to improve the pilot rating at low M_u and makes it impossible for him to accept the situation for normal operation as M_u increases. The introduction of a shaping network in the translational control providing pseudo-velocity control (velocity pusher) certainly improves this situation, as a comparison of Figs. 14 and 15 indicates.

It appears from the foregoing that the main advantage of the velocity pusher over the acceleration pusher is that the velocity pusher reduces the mismatching of the attitude and translation control by providing sufficient system lead to avoid divergent pilot coupling of the attitude and velocity modes. The translational control, properly shaped, would have merit from a handling qualities viewpoint, particularly on vehicles with appreciable M_u.

When X_u was varied with M_u, the comparison of Fig. 16 indicates that there was no appreciable effect on pilot rating, and the effectiveness of the velocity pusher was not impaired. Also, the changes associated with stick trim characteristics

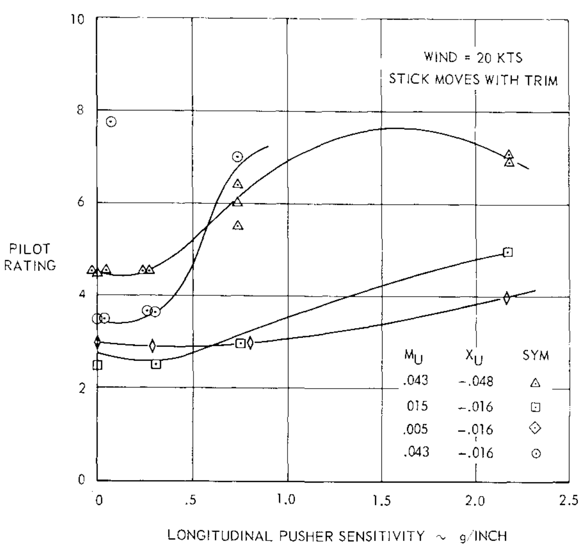

Fig. 12 Velocity pusher on attitude rate damped airframe.

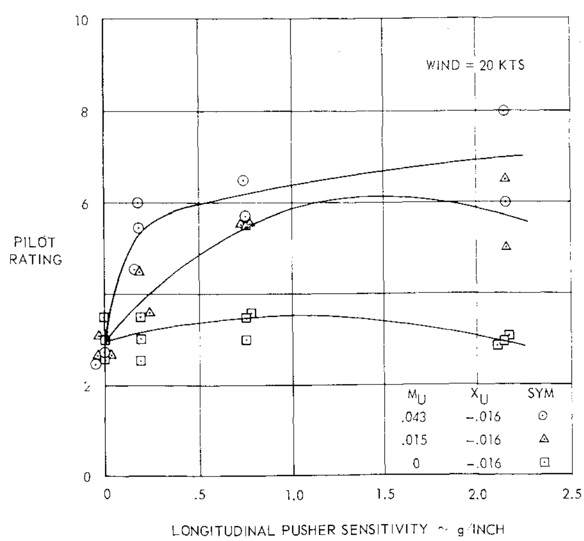

Fig. 14 Acceleration pusher on airframe with attitude stick steering.

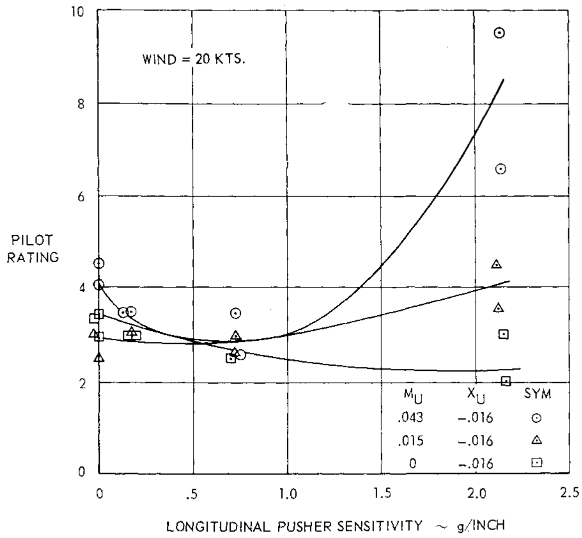

Fig. 15 Velocity pusher on airframe with attitude stick steering.

were investigated, and pilot's comments would indicate that there was no significant difference between the case where the stick was displaced with trim and the case where it was not.

Stabilized Platform

It became apparent in the work just discussed that it was difficult to take advantage of the translation control because of the interaction between attitude and translational velocity. The coupling that caused these difficulties was M_u. The fact that both attitude and translation were commanded by the same stick aggravated the problem. It seemed that, if attitude and translation could be controlled independently there would be a substantial improvement in the handling qualities. There were two ways of doing this: 1) provide separate control sticks for attitude and translation and 2) provide extremely tight autostabilization of attitude and cause the pilot to fly displacement (stabilized platform).

Because the pilot is using his left hand for lift control and his right for attitude control and is therefore not capable of manipulating a third-hand controller continuously, a decision was made to mechanize the autostabilized platform and restrain the attitude to zero. Acceleration and velocity pusher controls were then investigated on this stabilized platform. Figure 17 contains the results of these tests.

The acceleration pushers made possible a significant improvement in pilot rating over the best case, where the pilot was controlling displacement through changes of attitude using a stick steering type of control system. Although not shown on Fig. 17, large changes in X_u had only moderate ($\Delta PR = 0.5$) effect on handling qualities when using this acceleration pusher.

The use of open-loop shaping to give the pilot control of displacement through a velocity pusher caused a deterioration in handling qualities in the presence of the 20-knot winds used in the tests. Reduction of the wind component, as shown in Fig. 18, made pilot acceptability of the pusher possible, although the best pilot ratings were still slightly higher than with the acceleration pusher. Changes in X_u also had a greater effect on pilot rating when the velocity pusher was employed.

The fact that the velocity pusher is unsatisfactory in the presence of winds is explained as follows. In steady winds, there is a constant accelerating force on the airframe because of airframe and lifting system drag. With the velocity shaping network in the translation control system, it is not possible for the pilot to apply the constant force needed to counteract the winds and control his position. In the cases where the pilot had control of attitude through a stick steering control system, it was possible to supply the counteracting force by tilting the airplane, and under these circumstances the velocity pusher was rated acceptable or better by all pilots. With an acceleration pusher, it is possible to apply a constant accelerating force to overcome the steady wind forces and also to provide translation. It should be noted that it would be possible to design a velocity pusher with a residual acceleration component that could be used with the stabilized platform concept.

Conclusions

The various flight configurations tested are summarized in Table 2 and rated in detail on Figs. 10–18. The basis for evaluation of the various modes is pilot opinion. In all cases, there is satisfactory correlation among the ratings of the several test pilots.

The major influence on the pilot rating of the translational controls appears to be the occurrence of an interaction of the pushing effect with the variation in aerodynamic moment (M_u) as the velocity changes. The sense of the pitching moment is such that it normally opposes the stick movement

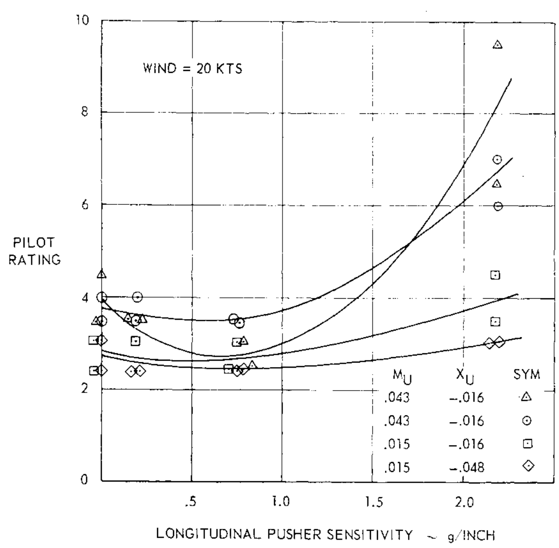

Fig. 16 Velocity pusher on airframe with attitude stick steering.

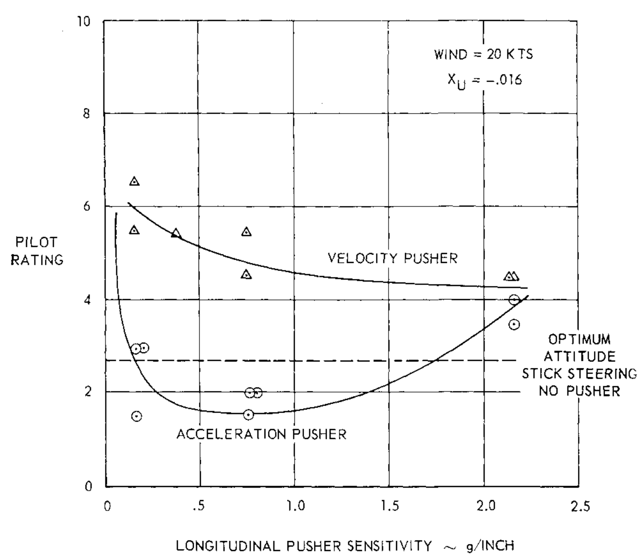

Fig. 17 Velocity and acceleration pushers on a stabilized platform.

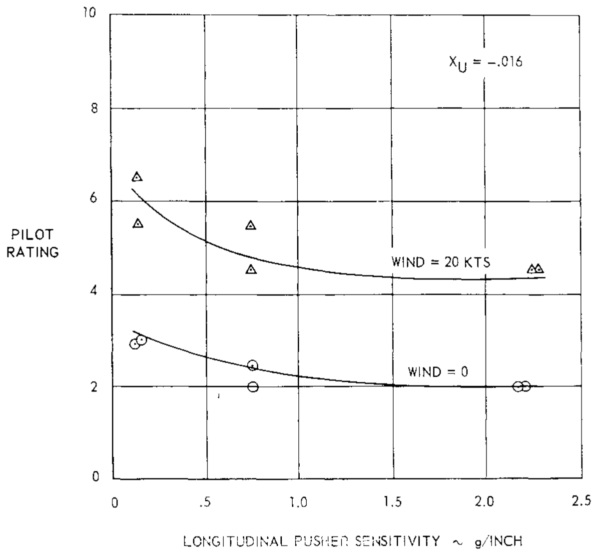

Fig. 18 Wind effects on a velocity pusher on a stabilized platform.

that causes the velocity change, but, for some levels of M_u and/or pusher effectiveness, varying amounts of control reversal occur. The undesirable interaction does not occur when the airframe is attitude stabilized and the M_u effect is eliminated. For this case, some levels of acceleration translational control received the best pilot ratings encountered in the test program. Velocity pushing is not satisfactory with the stabilized platform under wind conditions, since there is no way to furnish a steady force to counteract the wind, and the aircraft is quite literally "blown away."

With the airframe in the stick steering mode or with attitude rate damping, and for most levels of acceleration pushing, the interaction effect is prominent enough to cause unsatisfactory pilot ratings. For some lower levels of the velocity pusher and lower M_u, satisfactory pilot ratings are obtained. A factor influencing both types of controls is the high level of stick activity needed to accomplish the simulated flying task. In some cases, minimizing control movements makes it possible to fly successfully a configuration that would become uncontrollable with large stick inputs.

In summary, from an IFR handling qualities viewpoint, the following mixed control modes look promising: 1) acceleration pusher on a stabilized platform, and 2) velocity pusher with attitude steering.

Further work will be necessary to establish the maximum force levels that would be required of the pusher and the method by which it could be mechanized best on the airframe. The performance of the mixed control system will also have to be evaluated during transition, although it is anticipated that no adverse effects will occur. It is planned to investigate the use of pusher control for lateral maneuvering.

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