A DISCUSSION OF THE USE OF THRUST FOR CONTROL OF

VTOL AIRCRAFT

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SUMMARY

The use of engine thrust to control VTOL aircraft in hover has been examined to point out the importance of certain items that affect handling qualities. Information is based on the results of NASA-Ames Research Center tests using the piloted six-degree-of-freedom motion simulator and the X-14A variable stability and control aircraft. The discussion includes consideration of the use of thrust vectoring and thrust modulation. The results indicate that thrust vectoring to produce lateral translation can be used satisfactorily, reducing roll angular acceleration requirements. When thrust modulation is used for control, control lags must be minimized to avoid oscillatory tendencies.

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1. INTRODUCTION

Control of VTOL aircraft in hover and low-speed flight has been an important item in pacing the development of this type of aircraft. The required reaction forces for attitude control during hover have commonly been achieved by the use of engine compressor bleed air. This method, used on early jet lift VTOL aircraft such as the Shorts SC-1, Bell X-14A, and Lockheed XV-4, has been successful whenever a sufficient quantity of bleed air was available. More recently, particularly for larger VTOL aircraft such as the EWR VJ-101 and Dornier DO-31, engine thrust has been used directly for control. This method has the obvious advantages of improved efficiency and lighter weight, but when it is used, certain items should be considered carefully to insure satisfactory handling qualities. Handling qualities are affected by:

- Thrust vectoring authority
- Thrust response (engine time constant)
- Excess thrust for maneuvering
- Gyroscopic coupling
- Engine failure
- Cross coupling
- Ingestion and recirculation of exhaust gases

The first three items are basic to any configuration, while the last four depend on the configuration, and although important, will not be discussed in detail in this paper.

The purpose of this paper is to present some information, recently obtained by NASA, on the use of engine thrust for control of VTOL aircraft. Information is based primarily on the results of NASA-Ames Research Center tests using the piloted six-degree-of-freedom motion simulator and the X-14A variable stability and control aircraft.

2. RESULTS AND DISCUSSION

Thrust modulation and thrust vectoring are used in the following ways for control of VTOL aircraft: Roll and pitch moments as well as height can be controlled by thrust modulation while translation and yaw can be controlled by thrust vectoring. Because the requirements for controlling roll are generally demanding, the discussion has been

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oriented toward the roll axis. It should be recognized that the research thus far covers only the hover mode and further research studies should include the transition area.

2.1 Simulator Study of Thrust Vectoring

The proper use of thrust vectoring is important since angular acceleration control power may be reduced if, instead of tilting the aircraft, the pilot uses thrust for translation. A translational control has obvious advantages for large aircraft for which large amounts of roll inertia severely limit the angular response. The amount of translational acceleration desired must be defined as well as the method of controlling it. Preliminary information on a direct translational control system has been reported (1) and the method of control is shown schematically in Fig. 1. The control which employed a movable vane in the engine exhaust was investigated in two phases. Tests were first made in the Ames piloted multiaxis motion simulator (Fig. 2) and then in flight in the X-14A jet lift VTOL aircraft. The simulator tests sought answers to two questions: (1) how to control a lateral thrust vectoring vane from the cockpit (i.e., by a thumb controller or by stick deflection), and (2) how much to deflect the vane for satisfactory maneuvering. Answers to these questions were needed to expedite the flight test program.

2.1.1 Effect of type of controller.- Three methods of operating a controller were studied: (1) vane deflection commanded by the stick, (2) vane deflection proportional to bank angle, and (3) vane deflection by a thumb controller mounted on top of the stick. In the first method the vane was geared directly to the stick so lateral acceleration, A_y, was proportional to stick deflection. When pilots evaluated this method of control by a series of lateral quick stops and reversals, phasing problems between roll attitude and side acceleration occurred regardless of the gains. This control method could not be made satisfactory with a rate-damped system, and with an attitude command system the pilot did not have precise control during a roll reversal when side velocity was momentarily opposite to that normally associated with a given bank angle. In the second method, with side acceleration proportional to bank angle and an optimized rate-damped system, the control method was found to be satisfactory when the side acceleration for a given bank angle φ was increased by a factor of 1.5

$$A_y = 1.5(g \sin \varphi)$$

For the third method two types of thumb controller action, on-off (bang-bang) and proportional, were studied. The proportional thumb controller was preferred because of the pilot's desire to modulate side acceleration for "fine" control.

2.1.2 Effect of amount of side acceleration available.- The pilot rating of maximum amounts of side acceleration, for both the proportional and on-off thumb controller, are presented in Fig. 3. The preferred range was 0.08 to 0.13 g, depending somewhat on the type of controller used. The minimum for adequate maneuvering was 0.08 g while values greater than 0.13 g were uncomfortable for the pilot. As expected, the on-off controller was less satisfactory at the higher g values because the pilot tended to induce an oscillation (PIO) laterally as a result of the side force against his arm.

2.1.3 Effect of type of controller and maximum roll control power.- When the results from the simulator study of the various methods of control (Fig. 4) are compared with the conventional (vane inoperative) roll-to-translate method of control, two points are evident: (1) The vane improved (lower number) pilot rating; (2) programming the vane as a function of bank angle was not as desirable as actuating the vane by a thumb controller on top of the stick. The method of coupling side acceleration with bank angle had the obvious benefit of requiring smaller angular displacement and, hence, lower maximum angular acceleration ($\ddot{\varphi}$) to achieve a given side acceleration. When high values of $\ddot{\varphi}$ were used, however, the system was too sensitive and was rated slightly less desirable than the conventional system. The separate thumb controller was clearly easier to use for maneuvering sideways at the lower values of $\ddot{\varphi}$ and the pilot needed only a small amount of $\ddot{\varphi}$ to correct for inadvertent upsets. The pilot desired attitude stabilization in roll which would eliminate for all practical purposes any need for additional angular roll control ($\ddot{\varphi}$).

2.2 Flight Study of Thrust Vectoring

The flight evaluation of the side acceleration vane was made using the X-14A jet lift VTOL aircraft shown in Fig. 5. The close-up shows the vane control surface, complete with outrigger airfoils needed to improve effectiveness and reduce longitudinal cross coupling. The variable stability and control features of the X-14A permitted a systematic study to be made of the effect of variations in roll control power (angular acceleration) and sideward acceleration without the distraction of any cross-coupling effects such as roll due to vane deflection. A satisfactory value of roll damping was used for these tests. The evaluation maneuver consisted of a lateral translation of about two wing spans (approximately 70 ft) as well as flying around an obstacle course. These tests were made out of ground effect in calm air since only maneuvering aspects were to be evaluated. The proportional thumb controller method of regulating the vane, evaluated in the simulator studies, was essentially unchanged for the flight program.

2.2.1 Effect of side acceleration values.- The first series of flight tests were conducted to determine the amount of side acceleration desired for wings-level lateral offset maneuvers. The results (Fig. 6) indicate that A_y of the order of 0.03 g is acceptable and 0.10 g is satisfactory. In terms of the amount of time required to move sideward one wing span (33 ft), the foregoing A_y values correspond to approximately 13 and 7 sec, respectively. When low values of A_y were used, the response was too sluggish and too much lead time was required to maneuver precisely. Higher values of A_y (greater than 0.10 g) were desired when moving forward as well as sideways. In flat turns, however, at 20 knots forward speed, the maximum side force capability of the vane (0.15 g) was insufficient to offset the centrifugal force, and the pilot preferred to add bank angle. At the high A_y values, there was, of course, an appreciable thrust decrement and a consequent loss of altitude. This demanded adaptation since the pilot no longer could use bank attitude as a reference for height adjustment.

2.2.2 Effect of reductions in roll control power.- Data in Fig. 7 show how pilot rating changed as roll control power, $\ddot{\varphi}$, was varied. The flight results confirm the simulator tests in that less maximum angular acceleration was needed to obtain a satisfactory pilot rating when the vane was used to reposition the aircraft laterally. It should be recognized that in this case the pilot was not evaluating control power in the usual sense; roll control was used only to keep the wings level. As angular acceleration was reduced for the conventional (roll to translate) method of control, the airplane became too sluggish and the pilot used full control to speed up the repositioning. Consequently, pilot rating deteriorated because no control margin was available for correcting trim or upsets.

Several additional observations can be made from the data in Fig. 7 relative to the use of thrust for translational control. First, it was not possible to define the minimum $\ddot{\varphi}$ needed for maneuvering out of ground effect with the thrust vectoring (vane) system tested because additional roll control power was needed to fly in ground effect disturbances during takeoff and landing since the pilot could not select lower control power values ($\ddot{\varphi}$) in flight. It would be expected that lower values of $\ddot{\varphi}$ than those shown would be entirely satisfactory for the thrust vectoring control out of ground effect. With the rate stabilization available for the X-14A tests, the pilot had a combined task of translation and roll stabilization. If attitude stabilization were used, some very minimal angular acceleration would be required to allow the pilot to adjust bank angle for conditions such as touchdown on a non-level surface. A second point is that when a rate-damped SAS was used for landing and takeoff of the X-14A, roll control power could not be reduced below approximately 0.6 rad/sec^2 regardless of the type of control method used. In other words the disturbances due to ground effect cause attitude upsets that were not alleviated by the vane control method alone. For this reason, as well as to reduce roll disturbances introduced inadvertently by the pilot, attitude stabilization would be required with the vane control system. Finally, the difference between the lowest value of control power acceptable (0.6 rad/sec^2) and the value where the curves intersect (0.9 rad/sec^2) is an indication of the minimum amount of control power needed for conventional (roll to translate) maneuvering. Thus, 0.6 rad/sec^2 needed for ground-induced upsets and disturbances plus 0.3 rad/sec^2 required for minimum maneuvering, a total value of 0.9 rad/sec^2, represents the minimum total control power required to operate the X-14A aircraft with a rate-damped stabilization system. More than 0.9 rad/sec^2 is needed, of course, for more rapid maneuvering and for gusty air.

2.2.3 <u>Effect of vane response</u>.- Another factor to be considered in evaluating the thrust vectoring method is the time constant (response) of the control system. The system used had a first-order time constant of approximately 0.2 second. Although systematic tests were not conducted to evaluate their effects, larger time constants would probably degrade pilot opinion. In recent NASA Langley tests (2) to investigate height control requirements time constants greater than 0.5 second presented little problem during hovering (away from the ground); however, during landing the pilot had to alter his technique (to reduce overcontrolling) to allow a safe touchdown. It follows that, if precise sidewards maneuvering is needed (for operation in close quarters), low control system time constants are needed for the thrust vectoring system.

2.2.4 <u>Use of vectored thrust for larger aircraft</u>.- One can only speculate at this time from the limited testing on the X-14A how acceptable a lateral acceleration vane would be for larger aircraft. Other than the obvious advantage of easing the angular acceleration roll problem for high-inertia aircraft, it would appear logical that when hovering larger span aircraft near the ground, the pilot might prefer to use vectored thrust because he would have less tendency to strike a wing tip. To check this hypothesis the wing span of the X-14A was doubled, as shown in Fig. 8, by installing lightweight tubes and wing tips of orange-colored styrofoam spheres.

Three pilots then evaluated the thrust vectoring control as well as the conventional roll-to-translate method for the extended span aircraft in air taxi, quick reversals, and obstacle course maneuvers. Other than a barely perceptible tendency to hover at a higher altitude, none of the pilots preferred to use thrust vectoring for fear of hitting a wing tip in operational-type maneuvers. Apparently this simulation of size was too crude to result in meaningful conclusions. Although the tests generally showed no serious limitations to the use of the vane control, it was apparent that this type of control would be used more for air taxi type maneuvers (slow, relatively short distances). For quicker repositioning, the pilot would prefer to re-aline the aircraft in a flat turn. The flat turn maneuver requires training because the side forces are not natural. Further research should be conducted with the vane control in slow speed flight; however, as noted previously, attitude stabilization is needed to unburden the pilot and thereby allow a more accurate assessment of the vane control method.

2.3 Thrust Modulation

A slowly responding turbojet engine will require the pilot to lead the output to compensate for the sluggish behavior. Little information is available to aid in defining tolerable levels of engine time-constant for VTOL thrust modulation. Engine time-constant is of particular importance when larger thrust engines, such as the deflected cruise type, are used for control in hover and when fan thrust is controlled by varying fan rpm. There are two areas of primary interest to consider when thrust modulation is used for controlling VTOL aircraft: (1) the effect of thrust time constant on control requirements, and (2) the effect of reducing total lift when a control moment is applied. The following discussion primarily concerns the effect of time constant.

2.3.1 Effect of lag on control requirements.- Current control specifications (3) for VTOL aircraft are expressed in terms of an attitude change after a given time following a control input. It is shown in Fig. 9 that as control lag is increased, the moment needed to produce a given attitude increases, depending on the time increment. Since the attitude change for the roll axis is taken after 0.5 sec, it is apparent that even a low value of control lag (0.2 sec) doubles the required moment. The attitude change for the yaw and pitch axes is taken after 1 sec so the effect of lag on moment requirement is less severe.

2.3.2 Types of control lags tested.- There are two primary control lags of interest when engine thrust is used as part of the control system. These are the first-order and second-order lags whose characteristics are shown in generalized form in Fig. 10. The shape of the first-order-type curve is typical of large turbojet engines. In this case, the thrust response is dominated primarily by large rotary inertia. The initial response depends on the addition of fuel and the increase in exhaust temperature. The final steady-state thrust value is reached with no overshoot. The second-order system is typical of small lift engines with high thrust-to-weight ratios and lift fans.

The primary variables selected for the study on the piloted six-degree-of-freedom motion simulator were the time to reach 63 percent of the final steady-state value and the percent initial overshoot. Such nonlinear effects as actuator rate-limiting and control system inertia which affect control power requirements were not included in this simplified program.

2.3.3 Effect of first-order lag in roll control.- It was of interest to examine how different types of control systems were affected by first-order lags, since a more sophisticated control system might be more tolerant of poor thrust response. All the control systems used optimum values of control sensitivity and damping. Zero lag was maintained about the pitch and yaw axes. Results are shown in Fig. 11 for unstabilized (acceleration), rate-damped, and attitude command systems. A number of observations can be made from these results: (1) At zero time lag only the control systems with stabilization feedback loops were rated satisfactory, (2) lags could reach approximately 0.2 sec before stabilized systems were rated unsatisfactory, and (3) the more sophisticated (attitude command) system suffered more with the larger control lags. This poorer behavior is believed to be due in part to the fact that the response of the attitude stabilization system also contains a similar value of lag. For all types of control systems the pilots complained about the feeling of reduced damping and the tendency toward pilot-induced oscillations (PIO). As lag was increased, precise quick stops and reversals became more difficult and eventually even steady hovering became impossible. It can be shown in a closed-loop stability analysis that as loop gain is held constant and lag is increased, both frequency and damping are reduced and instability eventually results. In the simulator tests increasing the damping ratio of the attitude stabilization to the order of 1.5 reduced the oscillatory behavior, but with this high value of damping a sluggish response resulted in spite of the large control power used (2.0 rad/sec^2).

2.3.4 Effect of lag with increased control sensitivity.- Increasing control power to maintain the same bank angle after 1 second did little to improve the situation. As shown in Fig. 12, pilot rating still deteriorated as the PIO tendency remained. A nonlinear type of control system could possibly reduce the PIO tendency; however, tests to determine this effect were not conducted.

2.3.5 Comparison of first- and second-order lag systems.- The overall thrust response of lift engines is inherently more rapid than that of larger turbojet engines. However, depending on the degree of sophistication of the fuel control, there may be some overshoot of the steady-state value. Because the initial thrust response may not be rapid if the overshoot is reasonably low, the stability and piloting characteristics of a second-order system might be expected to be no better than that of a first-order system. The simulator results shown in Fig. 13 bear this out; the pilot again complained about PIO tendencies. There is essentially no difference in pilot rating between the two systems when the second-order system has a 3.5-percent overshoot which corresponds to a damping ratio of 0.7. The fact remains that with the type of characteristics shown, control with thrust-modulated lift engines should still be adequate since pilot rating is satisfactory below a response time of approximately 0.2 sec, well within the time response capability of current lift engines.

2.3.6 Effect of overshoot with second-order lag.- An additional consideration in the thrust modulation characteristics of some types of lift engines and also lift fans when used for control is the amount of tolerable overshoot. The results in Fig. 14 indicate that pilot rating deteriorates as overshoot percentage increases. These results were obtained with an attitude stabilized control system using a constant value of roll control lag of approximately 0.12 sec (to 63 percent). These larger values of overshoot are obviously undesirable and could be avoided by proper design of the fuel control system. In the case of lift fans, lead terms could be introduced with an electronic control to improve lag and reduce overshoot.

2.3.7 Thrust margin required for maneuvering.- When thrust modulation is used for attitude control for pitch or roll, a loss in altitude may occur unless sufficient excess thrust is available. Factors which affect the amount of excess thrust required to maintain altitude for a commanded change in roll attitude include the moment of inertia in roll, I_X, the distance between the engines and the roll axis, d, the weight of the aircraft, W, and the geometric distribution and excess thrust of the lift engines.

Tests were conducted on the piloted six-degree-of-freedom motion simulator to evaluate excess thrust requirements during moderately brisk lateral sidestep maneuvers. The results of the simulator studies are presented in Fig. 15, in terms of the usual pilot rating boundaries. Shown in the satisfactory region is the VJ-101 aircraft. It is shown that the amount of excess thrust required to achieve a satisfactory pilot rating increases rapidly as the parameter I_X/dW increases beyond 0.1. At the larger values of I_X/dW the pilot complained about the inability to maintain altitude during even mild roll reversals. Further studies need to be carried out on this problem to include pitch-roll coupling and the effect during transition.

3. CONCLUSIONS

The use of engine thrust to control VTOL aircraft has been examined to point out the importance of certain items that affect handling qualities. The following conclusions have been drawn from piloted simulator and flight tests related to the use of engine thrust for control by vectoring and modulation:

1. Limited flight tests showed no serious limitations to the use of a vane in the engine exhaust to vector thrust for sideways translation.

2. When using thrust vectoring directly to translate sideways the pilots preferred a separate proportional type controller mounted on top of the stick rather than direct gearing to the stick or programming the vane as a function of bank angle.

3. Values of lateral acceleration of the order of 0.10 g were satisfactory for normal sideways maneuvering. Values larger than 0.15 g are desired for moving forward and sideways.

4. Compared to the conventional roll-to-translate method, using the vane reduced roll control power requirements. It was necessary to provide only enough roll control power to adjust for wings leveling. Attitude stabilization in roll was needed to use the vane control method effectively.

5. When thrust modulation was used for control, simulator tests showed that control lags below 0.2 sec were satisfactory for stabilized

hover control systems. For the type of system used the attitude command system deteriorated more rapidly with increasing control lag than did the rate-damped system.

6. There was essentially no difference between pilot rating of first- and second-order lag systems, provided the initial overshoots for the second-order system were small.

7. Despite increases in control power to maintain a constant bank angle after 1 sec, pilot rating still deteriorated as control lag was increased.

8. Regardless of the type of control system used, the pilots complained about poor damping and PIO tendencies as control lag was increased.

4. REFERENCES

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2. Kelly, James R.; Garren, John F., Jr.; and Deal, Berry L.: "Flight Investigation of V/STOL Height-Control Requirements for Hovering and Low-Speed Flight Under Visual Conditions." NASA TN D-3977, 1967.

3. Recommendations for V/STOL Handling Qualities, AGARD Rep. 408, Oct. 1962.

TRANSLATIONAL CONTROL METHODS
X-14A

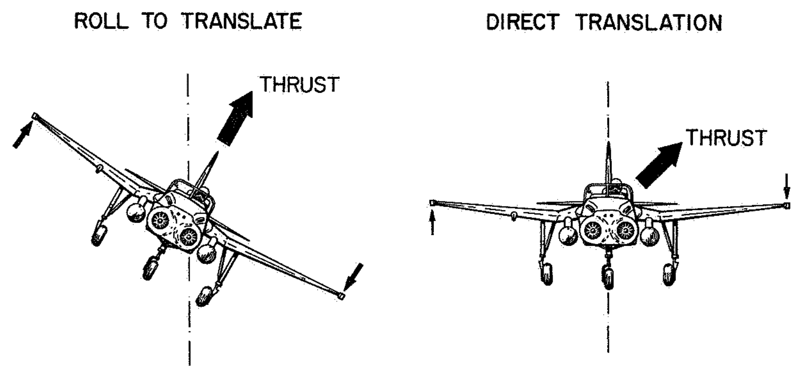

Figure 1.

SIX - DEGREE - OF - FREEDOM - MOTION SIMULATOR

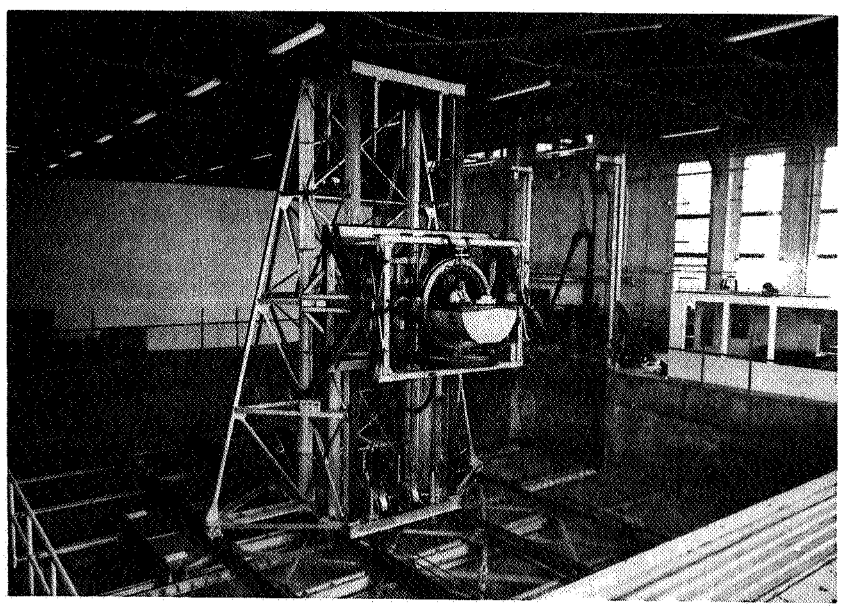

Figure 2.

EFFECT OF LATERAL ACCELERATION ON PILOT RATING
FOR TWO TYPES OF THUMB CONTROLLERS
SIX DEGREE SIMULATOR

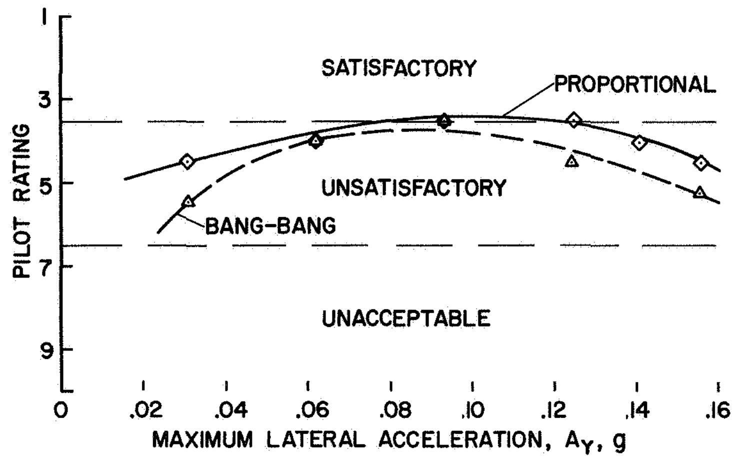

Figure 3.

EFFECT OF VARIOUS LATERAL CONTROL
METHODS ON PILOT RATING
SIX DEGREE SIMULATOR

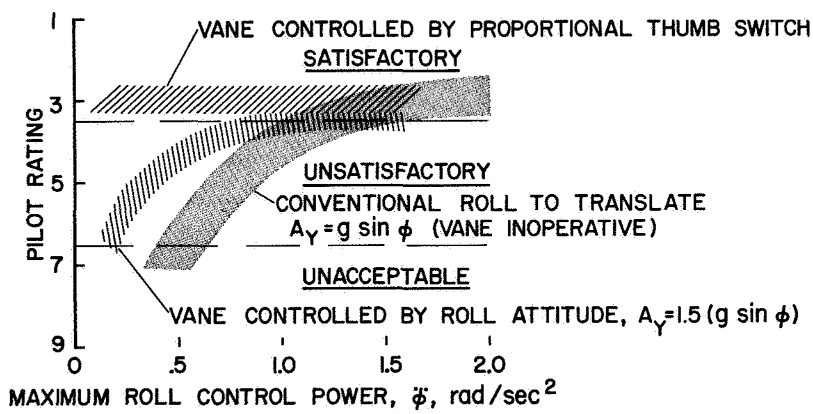

Figure 4.

X-14A VTOL AIRCRAFT EQUIPPED
WITH LATERAL ACCELERATION VANE

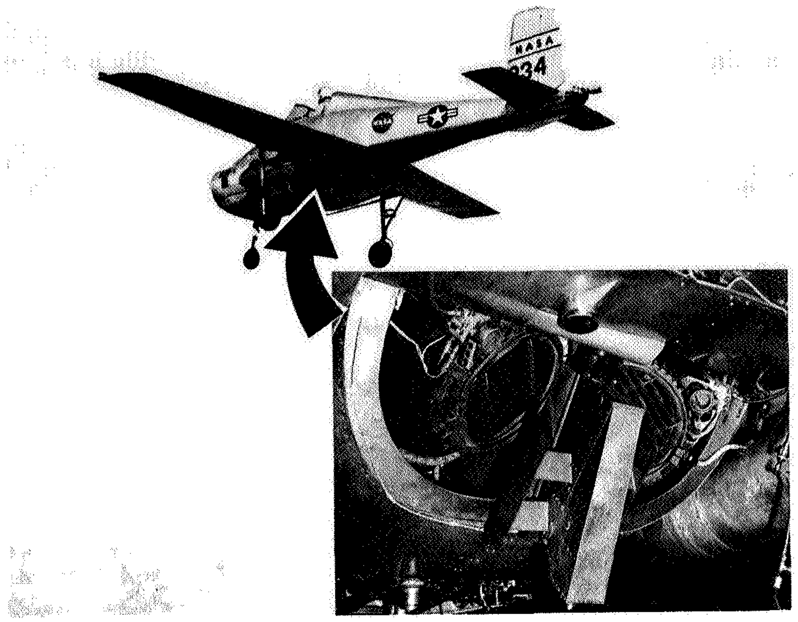

Figure 5.

EFFECT OF LATERAL ACCELERATION ON PILOT RATING
X-14A

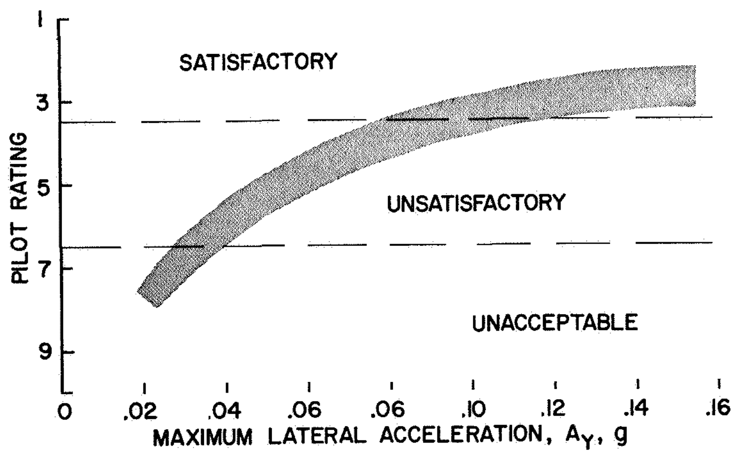

Figure 6.

COMPARISON OF VANE AND CONVENTIONAL ROLL CONTROL METHODS FOR LATERAL MANEUVERING
X-14A

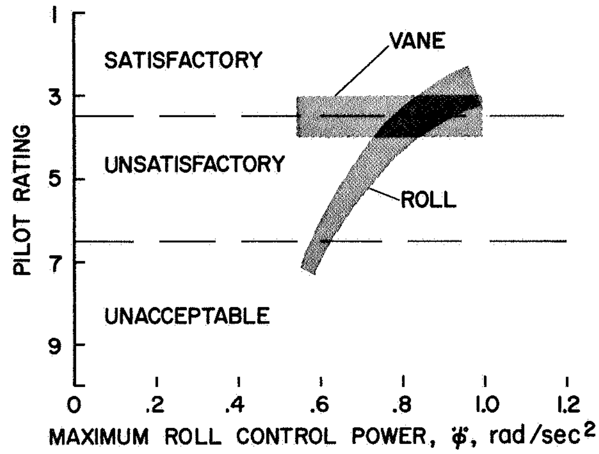

Figure 7.

X-14A VTOL AIRCRAFT WITH WING TIP EXTENSIONS

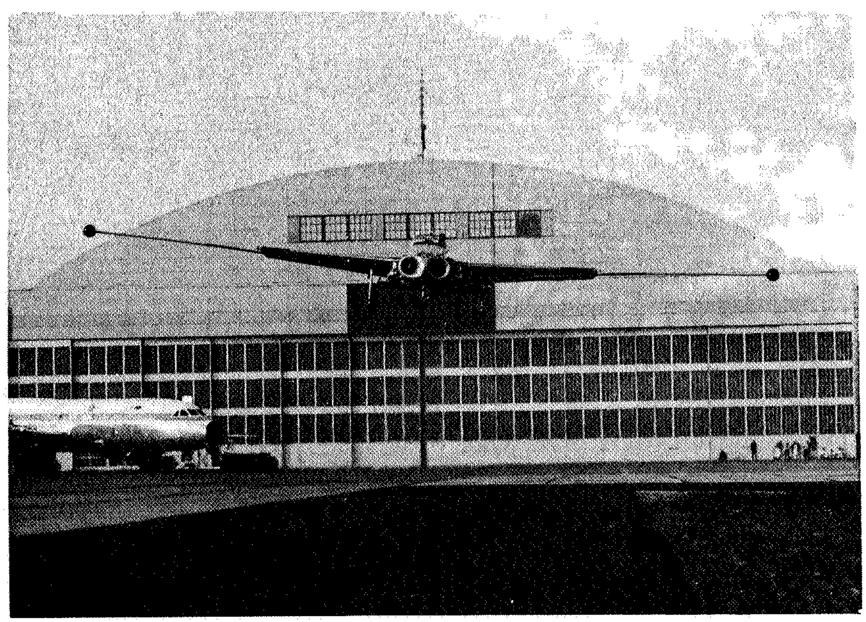

Figure 8.

EFFECT OF TIME CONSTANT ON MOMENT REQUIRED FOR ATTITUDE CHANGE

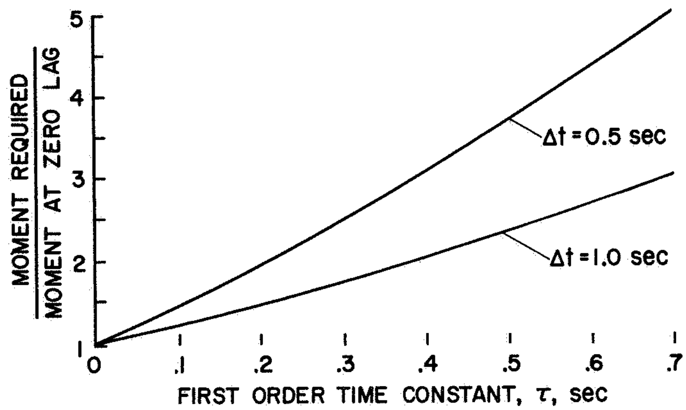

Figure 9.

TYPES OF CONTROL LAG TESTED

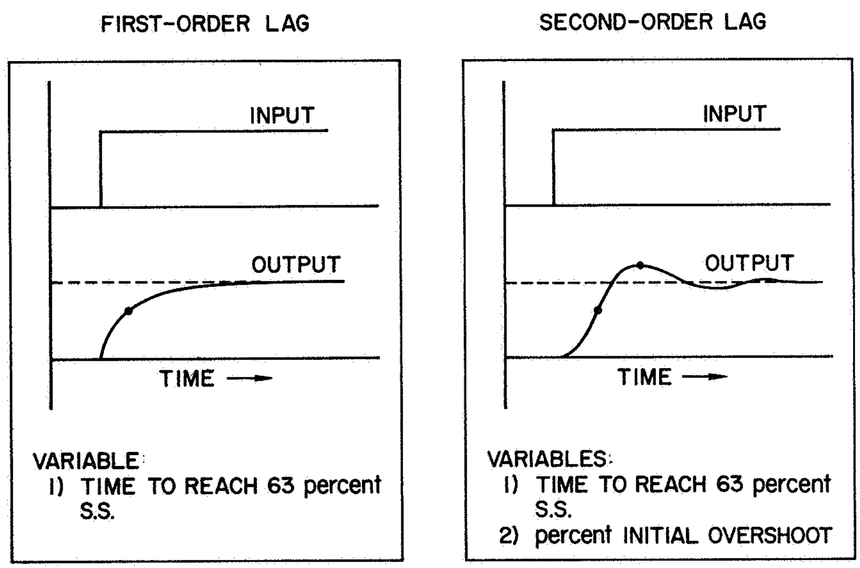

Figure 10.

EFFECT OF FIRST-ORDER LAG IN ROLL CONTROL
SIX DEGREE SIMULATOR

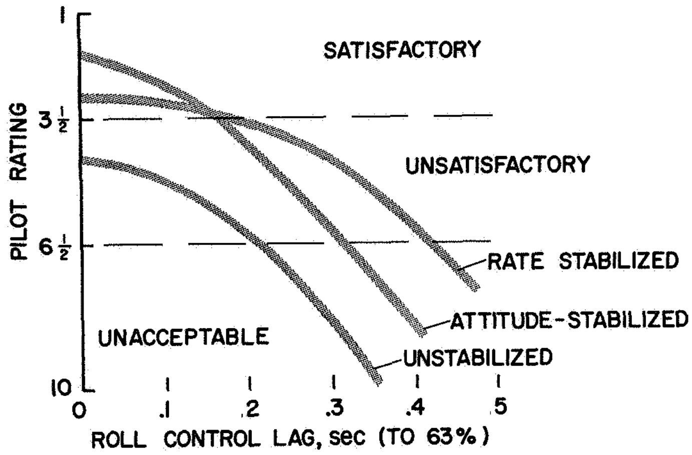

Figure 11.

EFFECT OF LAG ON PILOT RATING
(BANK ANGLE AFTER 1 sec KEPT CONSTANT)
SIX DEGREE SIMULATOR

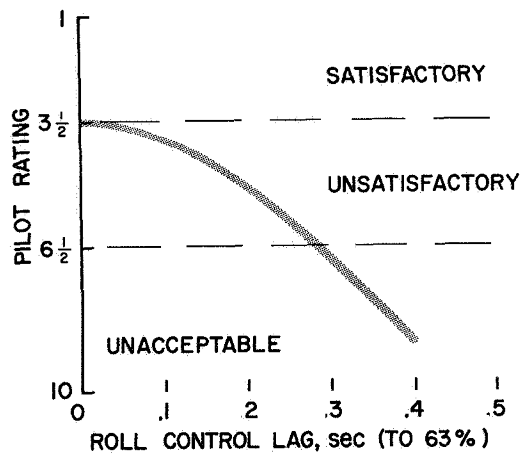

Figure 12.

COMPARISON OF FIRST- AND SECOND-ORDER LAG EFFECTS ON ROLL CONTROL FOR AN ATTITUDE-STABILIZED SYSTEM

SIX DEGREE SIMULATOR

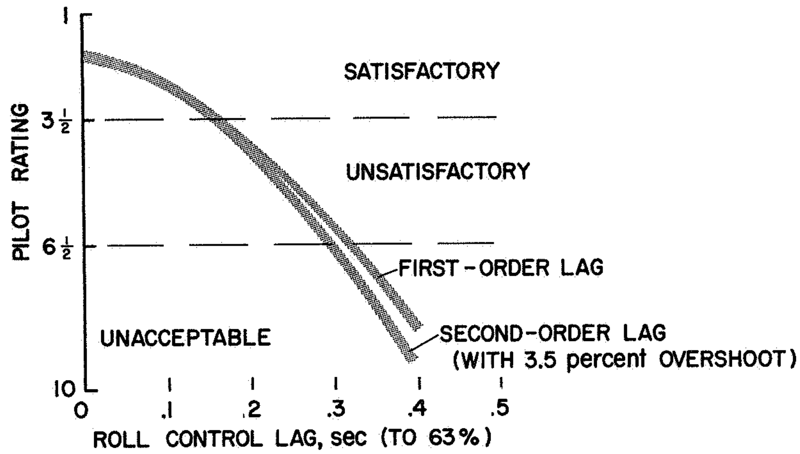

Figure 13.

EFFECT OF OVERSHOOT WITH SECOND-ORDER CONTROL LAG

SIX DEGREE SIMULATOR

ATTITUDE-STABILIZED SYSTEM

CONSTANT ROLL CONTROL LAG ≈ .12 sec (TO 63%)

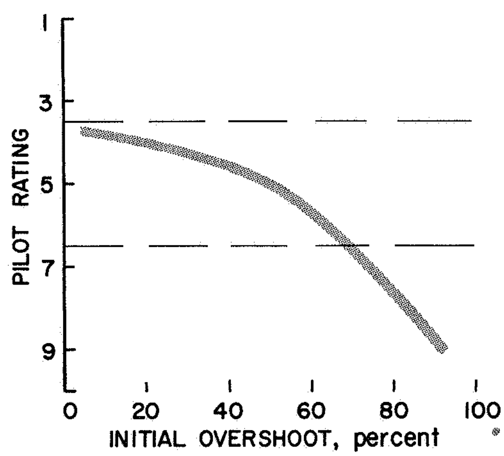

Figure 14.

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AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

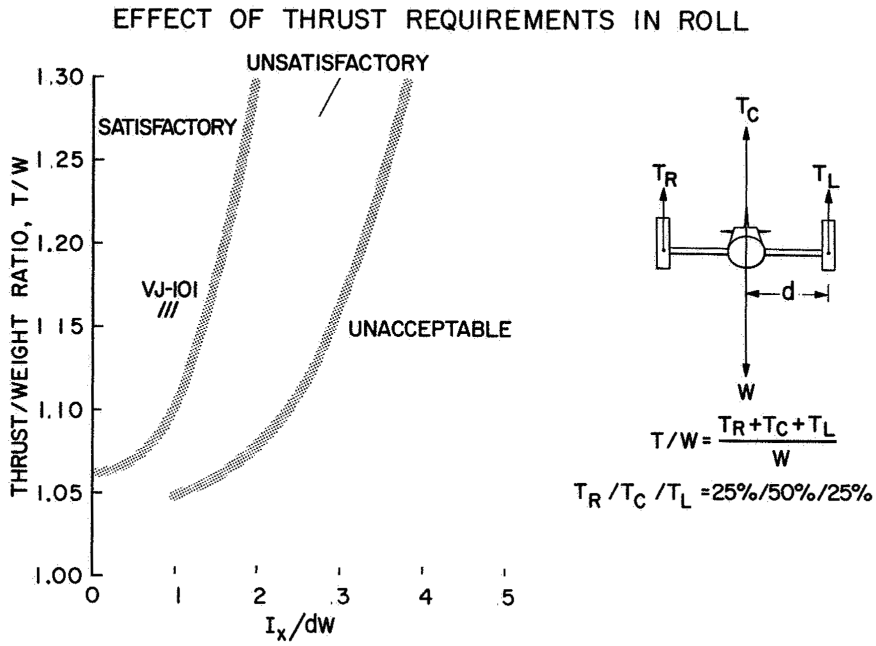
EFFECT OF THRUST REQUIREMENTS IN ROLL
UNSATISFACTORY
SATISFACTORY
VJ-101
UNACCEPTABLE
THRUST/WEIGHT RATIO, T/W
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0
1
2
3
4
5
I_x/dW
T_C
T_R
T_L
d
W
$T/W = \frac{T_R + T_C + T_L}{W}$
$T_R/T_C/T_L = 25\%/50\%/25\%$

Figure 15.