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AERODYNAMIC OBSERVATIONS FROM FLIGHT TESTS
OF TWO VTOL AIRCRAFT

By F. B. Gustafson, Robert J. Pegg, and Henry L. Kelley

Langley Research Center

INTRODUCTION

The purpose of this paper is to help bridge the gap between pilot experience and wind-tunnel or theoretical results by presenting flight measurements of aerodynamic characteristics for two types of VTOL aircraft. The experience thus represented is interpreted in terms of design philosophy for improvement. The two aircraft to be discussed are the tilt-wing (VZ-2) and tilt-duct (VZ-4) test beds shown in figures 1 and 2. The gross weights and horsepowers of these two aircraft are about the same; the tilt-wing configuration uses tail fans for control at low speeds, whereas the tilt-duct configuration uses the exhaust jet. In addition to the data obtained by NASA test pilots, some data have been included which were obtained by the respective company pilots while the programs were being monitored by NASA.

SYMBOLS

V	airspeed, knots
α_f	fuselage angle of attack, deg
i_w	wing incidence referenced to fuselage reference line, deg
δ_d	duct angle, referenced to fuselage reference line, deg
β	angle of sideslip, deg

DISCUSSION

Four phases of research are discussed: effects of ground proximity, wing-stall phenomena, aircraft pitching moments, and power-required variations. Additional information is included in the appendix on control moments, static stability, trim changes, and oscillations.

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The first point to be observed is that the approach to the ground can cause severe unsteadiness. Figures 3 and 4 show the behavior of the tilt-wing configuration in and out of ground effect, without any artificial stabilization, for a near-hovering condition. Note that the aircraft and control motions are moderate out of ground effect (fig. 3). For the aircraft in the region of ground effect (fig. 4), note that the aircraft and control motions are many times greater, with erratic angular velocity changes of about 10° per second and with frequent control motions of several inches. As has already been discussed in the paper presented by Robert O. Schade, the presence of the ground causes the slipstream to rebound and hit the tail surfaces, and this is at least a contributing cause to the instability. This problem can be expected to arise in practice for a variety of designs, especially when the aircraft are operated over uneven terrain.

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The use of airframe design changes, such as larger tail rotors, to damp these motions would, unfortunately, be expected to increase the erratic moments from the rebounding flow and perhaps even to increase the motions. Therefore, the best recommendation that can be offered now is the use of artificial damping to minimize the piloting problem. This damping was used with considerable success in the test aircraft.

The tilt-duct aircraft has thus far given little evidence of this type of unsteadiness, but there are indications of lateral instability from flow reflected from the ground. Piloting difficulty at certain heights has occurred in roll. Unstable rolling moments equal to about 1/3 of the available control moment have been indicated by rough measurements. Figure 5 shows a part of the mechanism of this instability. The aircraft was supported from a crane and was operated at fairly high power. Tuft grids were used to determine the flow paths shown. When the aircraft is banked, the upflow shifts to the wing which is already high. Since flow pressures as well as direction have a bearing on this problem, another check on the variation of moment with roll angle was made with most of the wing area removed. Unstable moments were no longer evident.

One step in the solution of such a problem would be the use of high-lift devices as a substitute for part of the wing area. Another step might be a modification to the planform.

The next topic of this discussion is the wing-stall phenomena; these effects have been mentioned in several papers. Figure 6 shows a sample flow pattern for the tilt-wing aircraft. Separation is indicated over a considerable area for this marginally acceptable flight condition. For the more extreme, unacceptable conditions, as shown in figure 7, the flow remained smooth over only a small area (near the tip at the leading edge).

The expedient of leading-edge droop as an approach to cleanup of the flow produced successive improvements in the flow for part-span and full-span coverage. Figures 8 to 10 show the successive shifts in rate of descent boundaries. Figure 8 is for the basic wing. The shaded area marked "poor" represents a region of difficult but feasible flight. The area beneath the solid lines is considered unacceptable; in fact, dangerous. The regions to the right and above are acceptable. Figure 9 shows the results for the outboard leading-edge-droop installation. Note that the peak of the boundary drops from climb at 500 feet per minute to just under level flight. In figure 10 for the full-span leading-edge droop, considerably more improvement is noted, with the peak down an extra 500 feet per minute; it is thus apparent that both inboard and outboard areas are important.

With leading-edge droop, not only were the "unacceptable" boundaries lowered, but flying in the "poor" areas was made far easier. Incidentally, the power required was reduced by an average of about 5 percent over this range of airspeeds with this approach to separation control.

These separation effects can be controlled either by high-lift devices and other approaches to flow control or by increasing wing area. Consideration of overall low-speed flying-qualities effects indicates that high-lift devices or flow control are preferable to a wing-area increase; in fact, wing-area decrease appears attractive if these flow-separation problems can still be handled. For example, two points are covered in more detail in the appendix; the undesirably high value of speed stability and the related short period of the longitudinal oscillations would (at low speeds) be aggravated by adding wing area and would be relieved by reducing it.

Further consideration is now given to leading-edge droop. It is not to be implied from one success with this device that a thorough understanding of this flow-separation problem has been attained. The leading-edge camber, as such, should not have been nearly so effective as is indicated, and the changed position of the leading edge relative to the propeller axis may have had a material effect on the results.

For the tilt-duct aircraft, this flow-separation problem is of far less concern, but interesting effects do occur for this type also (fig. 11). The duct angle for this test was 50°. This outboard flow separation was observed in level flight at a moderate wing angle of attack, about 7°, and is in keeping with other observations which indicated that the duct produced considerable upflow on the wing. This upflow is believed beneficial to performance, especially if flow separation can be minimized. Some adverse effects of the flow separation on flying qualities were noted, but some of these would be avoided if the aileron action were irreversible. Both the flow separation and the effects on flying qualities increase with increased rate of descent. Rates of descent up to 1,200 feet per minute are usable as is, at approach speeds. To further improve the descent characteristics, and also to avoid rapid roll-off when aircraft stall is encountered, some form of flow-separation control, probably including leading-edge slots or the equivalent over the outer part of the wing, again appears desirable.

The nose-up pitching moments during decelerating flight are next considered. These moments have been a problem with successive types of low-speed aircraft for over 20 years and deserve specific and continued attention from designers. The tilt-wing configuration has shown a reasonable control margin in the recorded data, although pilots' comments indicate a problem in rapid decelerations at low speeds. Power-available limitations have prevented recorded data from being obtained on this point, but study of the control and trim characteristics points up the need for an increase in control moment available as one means of improvement.

For the tilt-duct aircraft, figure 12 shows a pitching-moment problem. These results are representative of a decelerating transition; the decrease in airspeed in this interval of approximately 1 minute was obtained by an increase in the duct angle as shown. The aircraft angle of attack is seen to increase. The important point is that the longitudinal stick position moves slowly forward and, at low speeds, is essentially full forward, even though the nose was allowed to rise. Records of this type will vary in detail but show, in effect, that pilots have at best roughly no control margin under generally favorable circumstances; whereas, if the aircraft is to be handled in gusts or is to make short landings, a decisive margin of control is needed, as is recommended in the paper by Robert J. Tapscott. For this case, the longitudinal-control power is, in its own right, high enough. It is therefore recommended that the moment be reduced at its source, namely, at the ducts. Both tunnel and flight measurements have shown the ducts to be the source of this moment, and the previous paper by Paul F. Yaggy and Kenneth W. Goodson covers this point in some detail. Since the problem arises in large measure from normal force at the duct lip, one major step appears to be to shift the duct so that the lip is closer to the pivot axis; this axis would remain near the wing quarter-chord line and the aircraft center of gravity. Current tests of this aircraft at Langley involve use of moment-offsetting vanes in the rear portion of the ducts, so linked as to change angle as the ducts are rotated relative to the fuselage. As was shown in the previous paper by Yaggy and Goodson, such vanes can logically be used to handle part of the moments. The use of the vanes as the only device is, however, primarily an expedient to permit more control margin under favorable conditions. Such vanes should not be used in the future as the only device, because they will not relieve the pitch-up moments caused by gusts or by rapid maneuvers. Incidentally, the use of such vanes differentially is recommended as a powerful source of much-needed yaw control.

The final item for consideration is power required, relative to potential gains suggested by effects shown for varying the aircraft attitude at given wing or duct angle. This effect is relatively small, and also less fundamental in origin for the tilt-wing configuration, and therefore results for only the tilt-duct aircraft are presented. Figure 13 includes data that have been presented in the previous paper by John P. Reeder, which indicated the favorable flying-qualities significance of the short, constant-duct-angle curve. The added point to be made from figure 13 is that there is a large effect of attitude on power required at a given airspeed. The horsepower required is seen to be considerably less for the 10°-attitude curve than for the level-attitude curve ($\alpha_f = 0^{\circ}$). This power saving is shown not only as cruise flight is approached, where it would certainly be expected, but also at much lower airspeeds. Figure 11 showed separated flow over part of the wing at a moderate angle of attack; performance gains are shown in figure 13 to continue to higher angles of attack before large amounts of separation eventually limit the gains. It follows that use of high-lift devices, including flaps, should materially shorten take-offs and landings for the tilt-duct aircraft, since more load could be transferred to the wing without the aircraft getting too close to the angle for serious stall effects. Any increase in the usable length of the fixed-duct-angle curve obtained by such high-lift devices would also provide more freedom of piloting action in a steady approach at a fixed duct angle.

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CONCLUDING REMARKS

Suggestions have been made concerning V/STOL design philosophy for taking greater advantage of favorable power-required effects and for dealing with the problems resulting from ground proximity, from flow-separation effects, and from pitching moments arising in decelerating flight. Perhaps the most general observation to be drawn from this material is the desirability, at this stage of development, of exploiting potential flying-qualities and performance gains by use of high-lift devices or by other ways of getting more lift from less wing area.

APPENDIX

MEASURED CHARACTERISTICS OF TILT-WING AND TILT-DUCT CONFIGURATIONS

This appendix presents a number of additional measured characteristics of the VZ-2 and VZ-4 test aircraft. It should be noted that, except where otherwise stated, no automatic stabilization was used when the data presented were obtained.

Stability

Speed stability.- The speed stability variation of longitudinal-control position with airspeed for each of several fixed wing angles and constant power positions is shown in figure 14 for the tilt-wing aircraft. The steepness of the slopes at the low-speed wing settings indicates that large pitching-moment changes will be experienced with inadvertent changes in airspeed; for example, in gusty air and during longitudinal oscillations. Pilots' comments indicated that flatter slopes would result in more favorable flight characteristics.

Longitudinal oscillations.- Sample oscillations resulting from deliberate disturbances (longitudinal pulse input) on the tilt-wing aircraft are shown in figure 15. In the hovering configuration ($i_w = 85^\circ$), the response is essentially a simple, rapid divergence, though in a direction opposite to the input. At moderate speeds ($i_w = 40^\circ$), a lightly damped motion of undesirably short period is indicated. At cruise speeds ($i_w = 9^\circ$) the oscillation is well damped, but still of short period. It should be possible to improve the low-speed characteristics by reduction in speed stability (for example, by reduction of wing chord) and by increased damping of the aircraft.

The corresponding variation of the longitudinal oscillation period with airspeed is shown in figure 16.

Angular velocity response to longitudinal pulse inputs for the tilt-duct configuration are presented in figure 17 for duct angles of 7°, 20°, and 50°. In all of these conditions, pilots' comments indicated that the damping was very good, as confirmed by data presented in figure 17.

Static directional stability.- The static directional stability characteristics of the tilt-wing aircraft are shown in figure 18. The unstable (center) portion of the curves is believed to be caused, at least in part, by interference of the bifurcated exhaust pipe (and the exhaust flow) with the airflow over the vertical tail. Tuft surveys showed the portion of the tail behind the exhaust flow to be ineffective. Oval (flattened) tail-pipe assemblies have been designed and are expected to reduce this problem.

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The static directional characteristics of the tilt-duct configuration are shown in figure 19. According to pilots' opinion, this plot is typical for a range of duct angles of at least 0° to 50°. The curve shows the static directional stability characteristics to be stable; however, at a left sideslip angle of about 8° there is a small region of instability as indicated by the curve.

Dihedral effect.- A positive dihedral effect is shown in figure 20 for the tilt-wing test bed. At the high end of the speed range, the tilt-wing aircraft exhibits a strong lateral static stability, whereas at lower speeds this effect is decreased.

A sample curve, showing the dihedral effect characteristics of the tilt-duct configuration, is presented in figure 21. Pilots' comments indicated that the dihedral effect was so strong, for a range of duct angles of at least 0° to 50° in right sideslip, that he ran out of aileron control before rudder control was exhausted.

Control

Control power.- Control moment per inch of stick deflection in the near hovering configuration for the tilt-wing aircraft was considered marginal in yaw, adequate in pitch, and excessive in roll. In the paper by John P. Reeder, values of control power are given for the tilt-wing and tilt-duct aircraft in the hovering configuration.

Angular velocities in roll.- Maximum roll velocities encountered in hovering flight on the tilt-wing test bed, according to existing criteria, are greater than is desirable. No reason was found for not reducing materially the control power in roll; an alternate solution, however, which would permit retaining the moment available, would be to use a damper on the control stick. In figure 22, the maximum roll rate per inch of stick motion is plotted as a function of trim airspeed.

Yaw fan thrust.- The yaw-fan thrust variation with pedal displacement for the tilt-wing aircraft is shown in figure 23. These nonlinear control characteristics (particularly those near neutral) are objectionable to the pilots in this case, as in past aircraft experience.

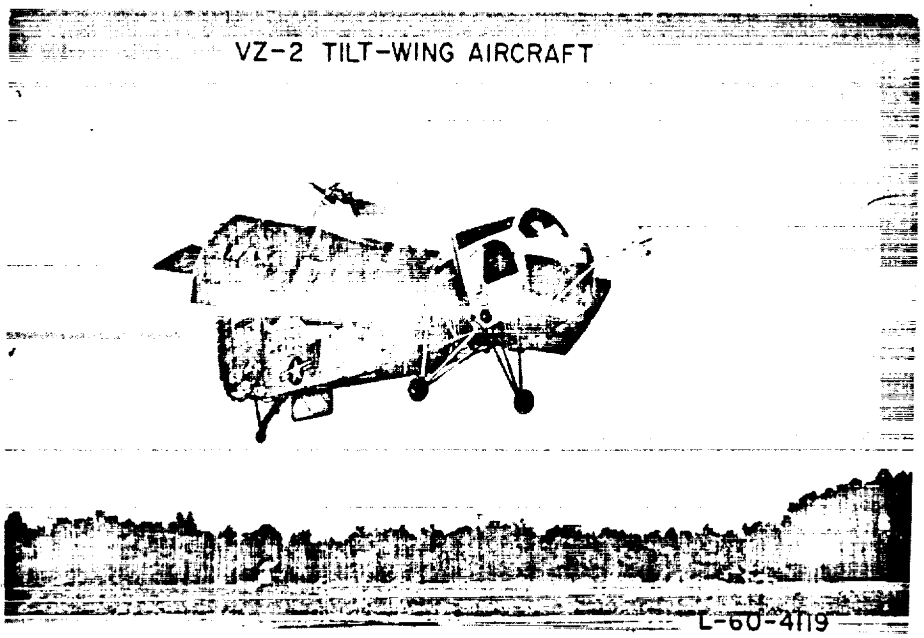
Trim

Longitudinal trim change with airspeed.- For fixed fuselage attitude of 0° and also for a fuselage attitude variation up to 10°, figure 24 shows the corresponding longitudinal stick position changes over flight range of the tilt-wing VTOL aircraft. The varying flight attitude is shown to require materially less change in longitudinal stick than the 0° fuselage flight attitude.

Wing angle of attack as a function of airspeed.- Figure 25 gives the variation of wing angle of attack of the tilt-wing aircraft with trim level-flight airspeed. Fuselage attitudes ranged from 0° to ±10°; these variations did not introduce appreciable scatter.

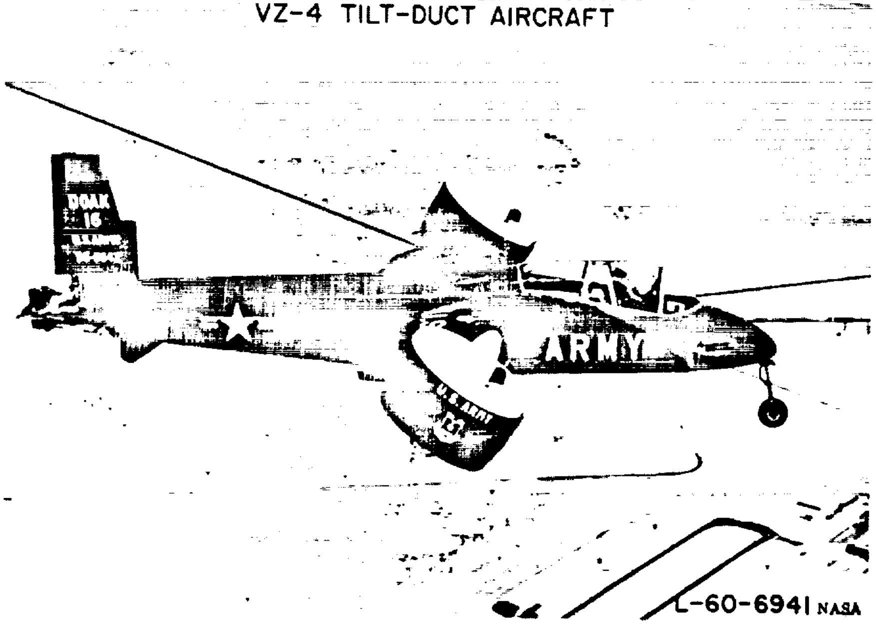
Power Required

In figure 26, power required for level flight of the tilt-wing aircraft is given as a function of trim airspeed. The test points spotted below the power curve indicate the power required for the aircraft with full-span drooped leading edges on the wings.


VZ-2 TILT-WING AIRCRAFT

L-60-4119

Figure 1


VZ-4 TILT-DUCT AIRCRAFT

L-60-6941 NASA

Figure 2

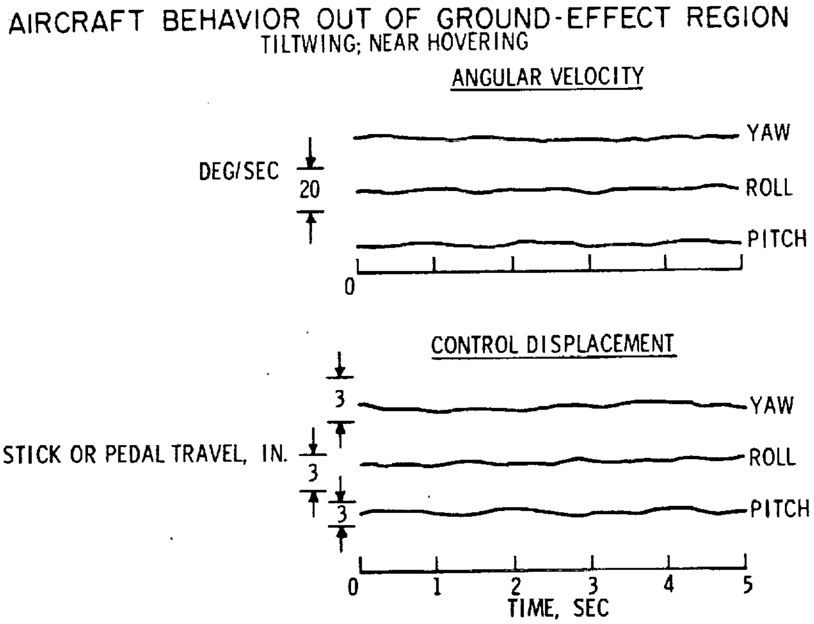


Figure 3

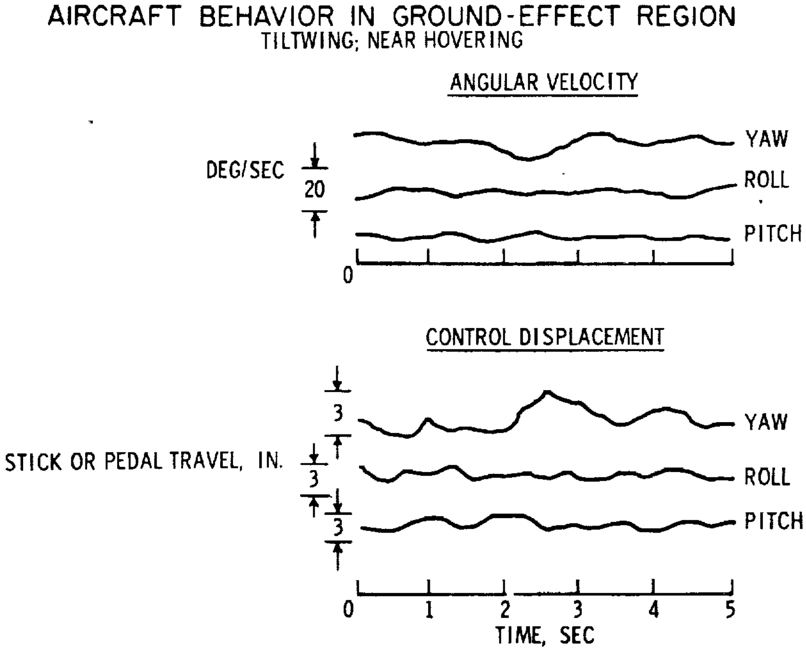


Figure 4

SOURCE OF DESTABILIZING GROUND EFFECT

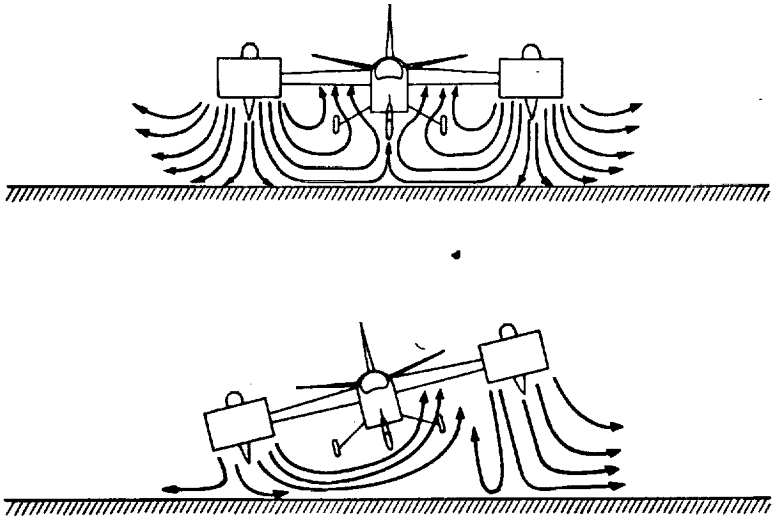


Figure 5

PARTIALLY STALLED WING

40⁰ WING ANGLE

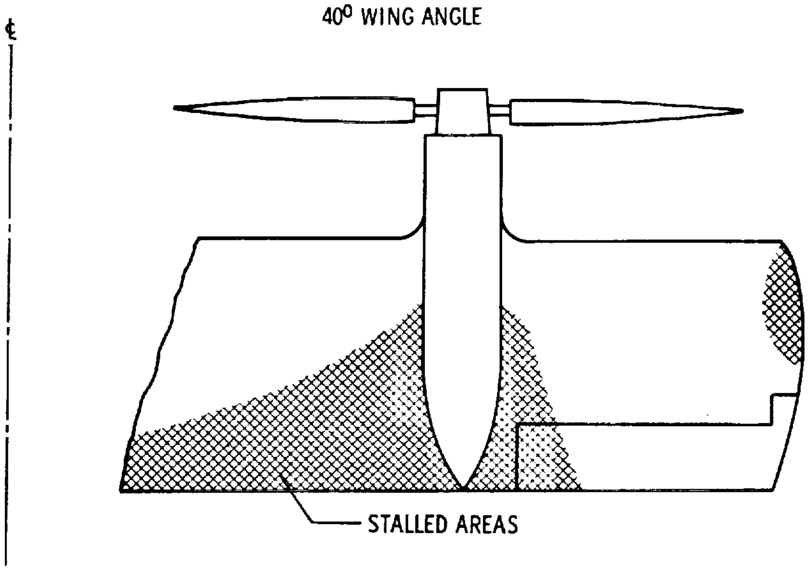


Figure 6

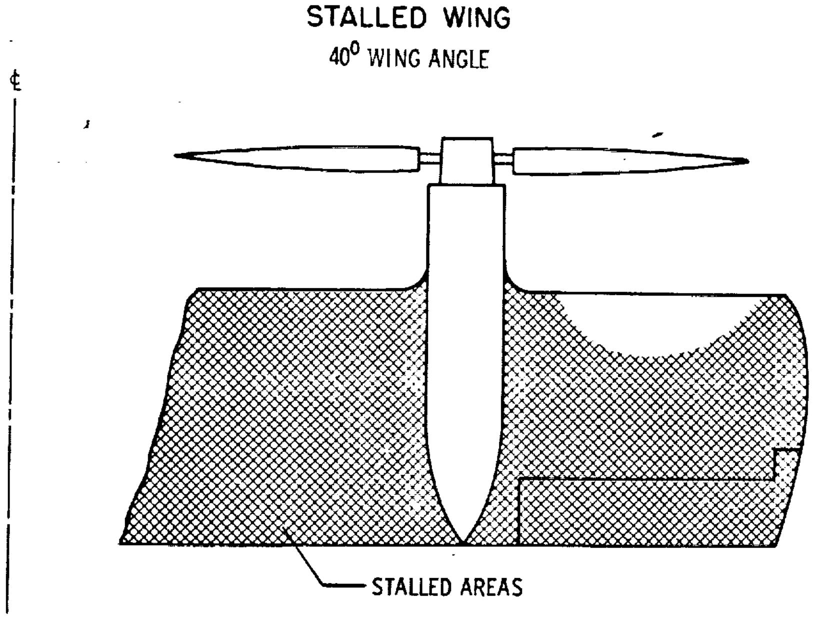


Figure 7

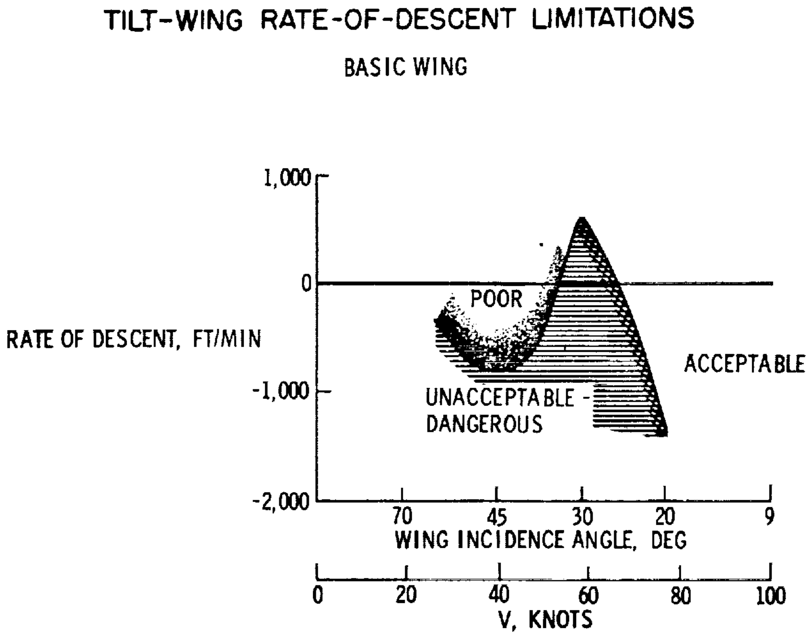


Figure 8

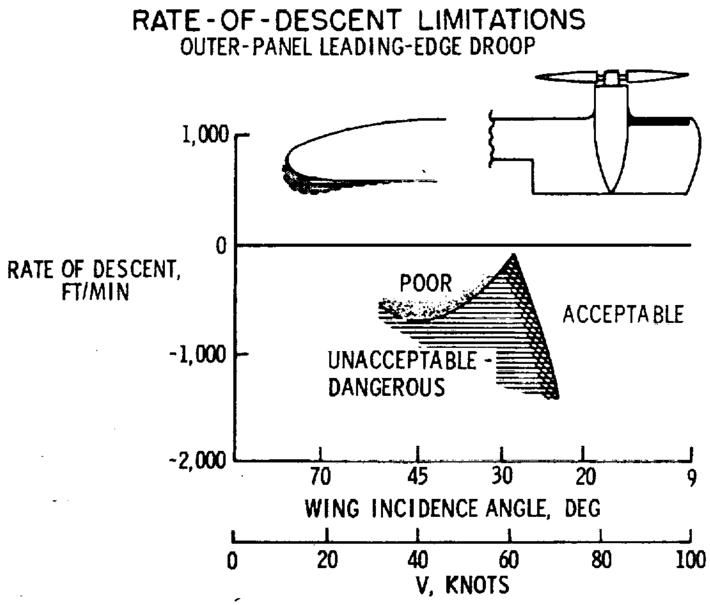


Figure 9

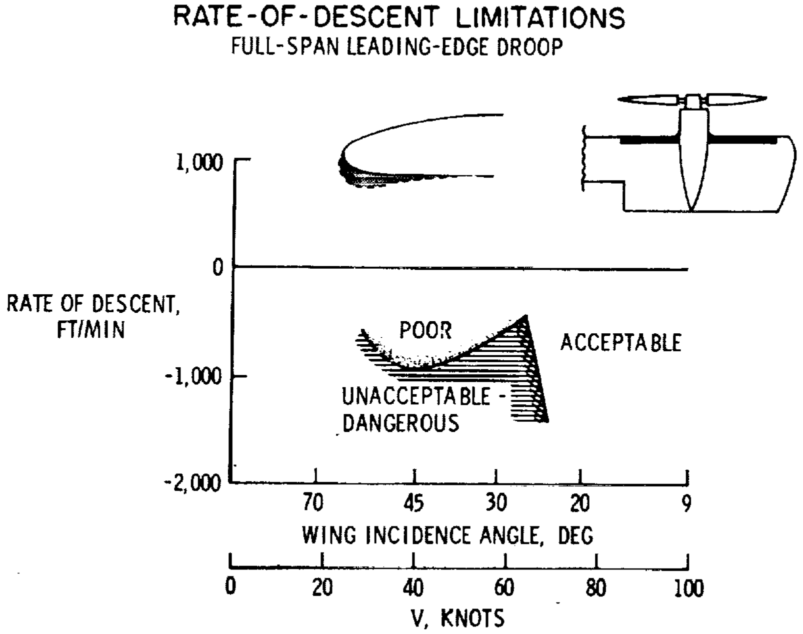


Figure 10

FLOW SEPARATION NEAR DUCT

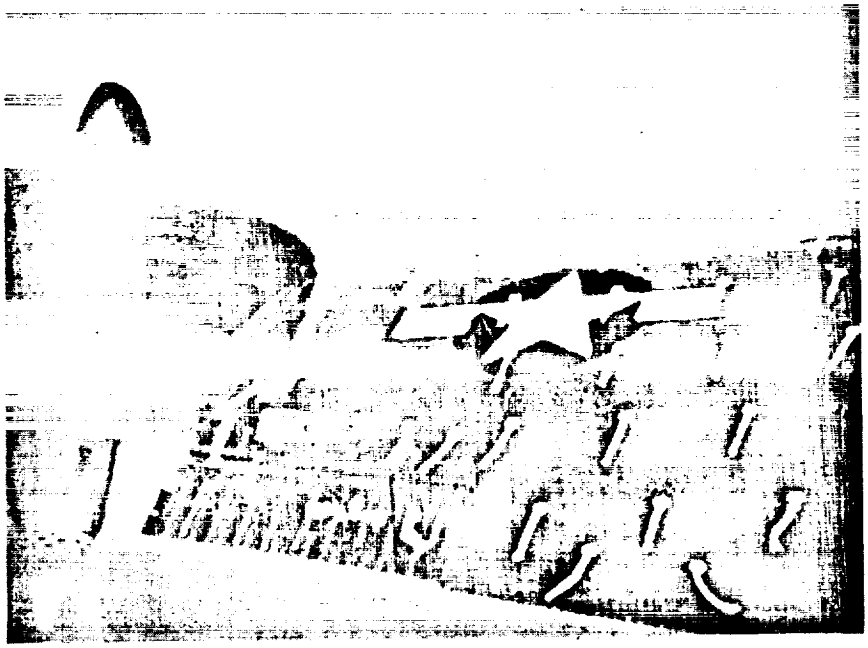


Figure 11

LONGITUDINAL CONTROL IN TRANSITION

TILT-DUCT AIRCRAFT

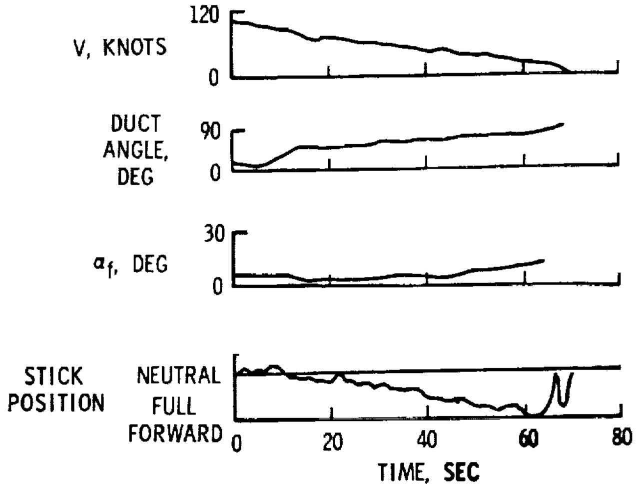


Figure 12

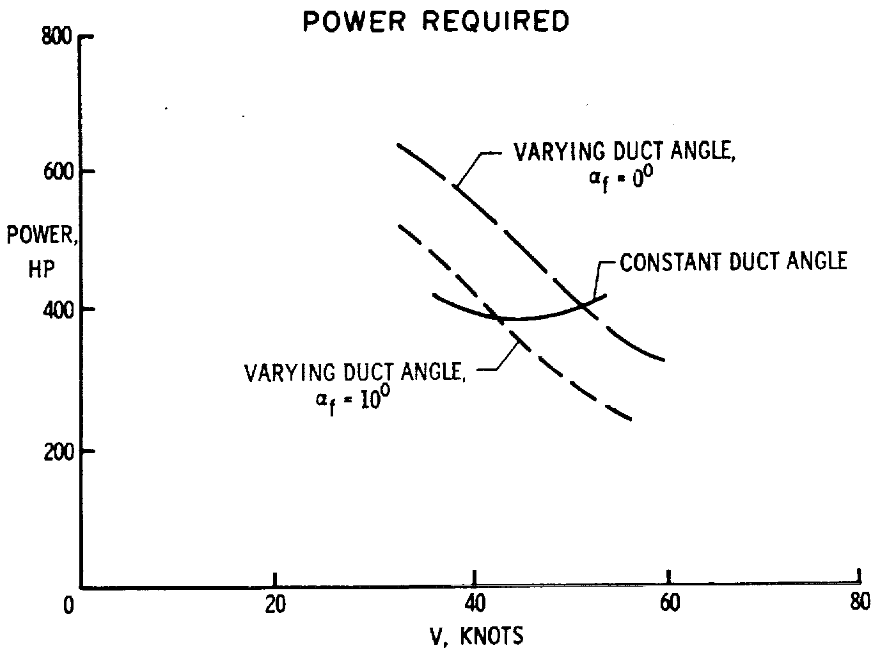


Figure 13

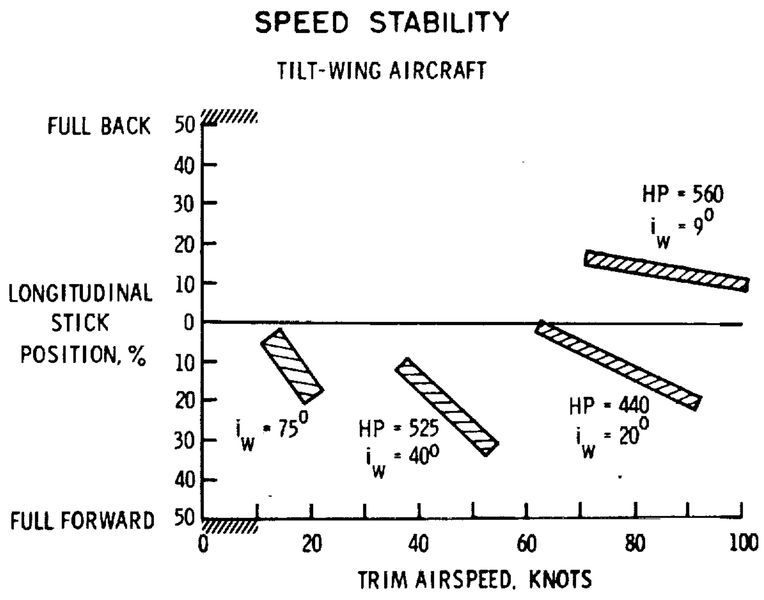
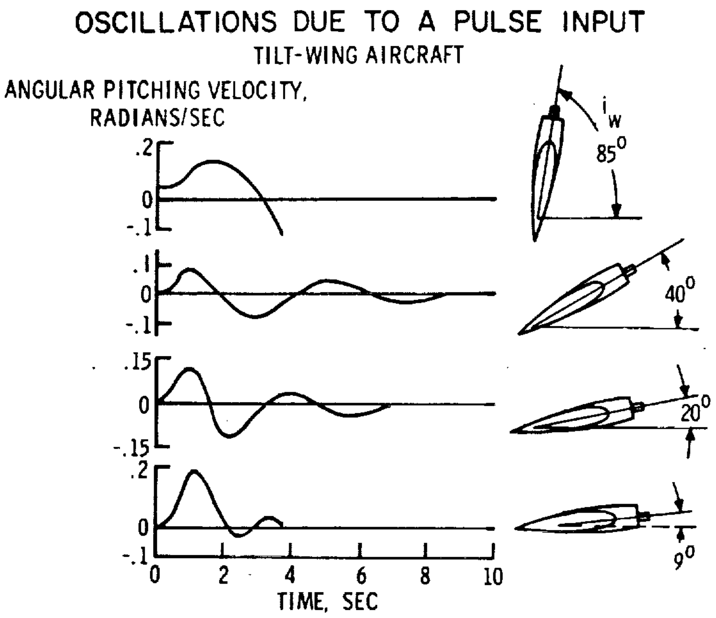
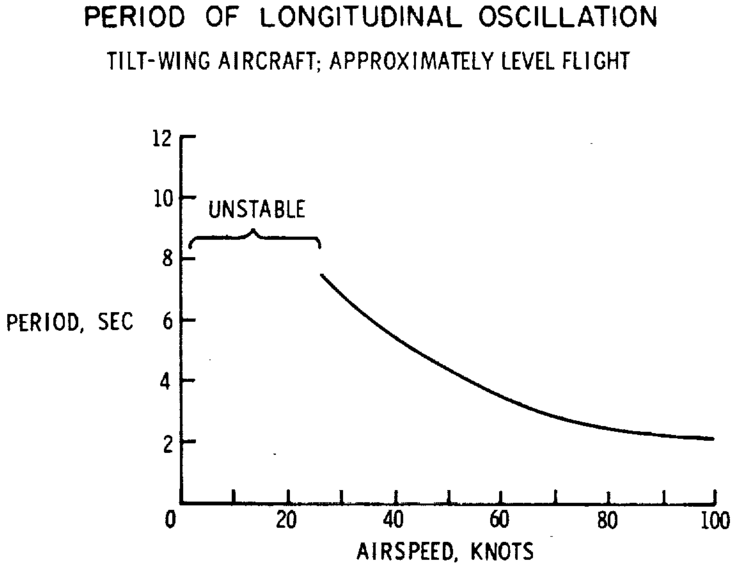


Figure 14


OSCILLATIONS DUE TO A PULSE INPUT

TILT-WING AIRCRAFT

Figure 15


PERIOD OF LONGITUDINAL OSCILLATION

TILT-WING AIRCRAFT; APPROXIMATELY LEVEL FLIGHT

Figure 16

OSCILLATIONS DUE TO A PULSE INPUT

TILT-DUCT AIRCRAFT

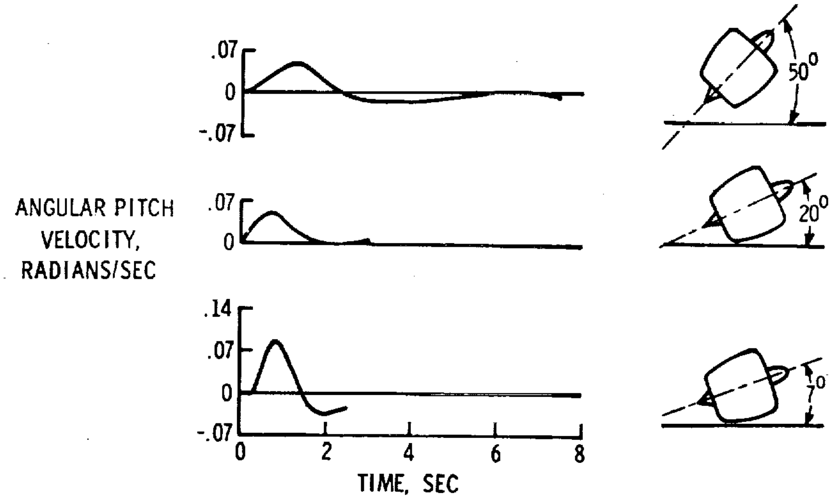


Figure 17

STATIC DIRECTIONAL STABILITY

TILT-WING AIRCRAFT

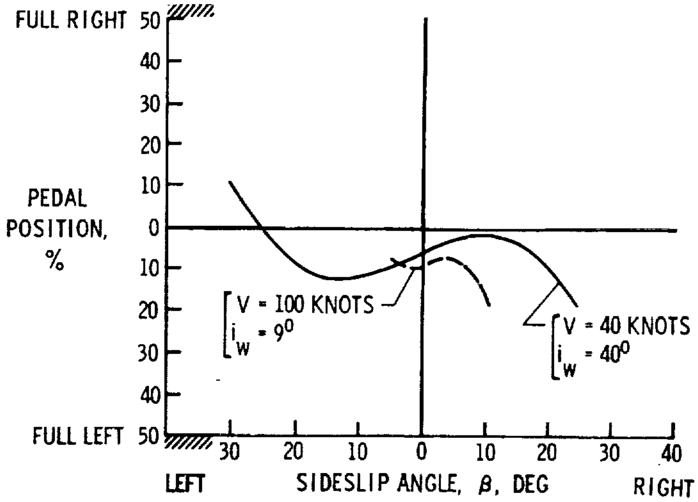


Figure 18

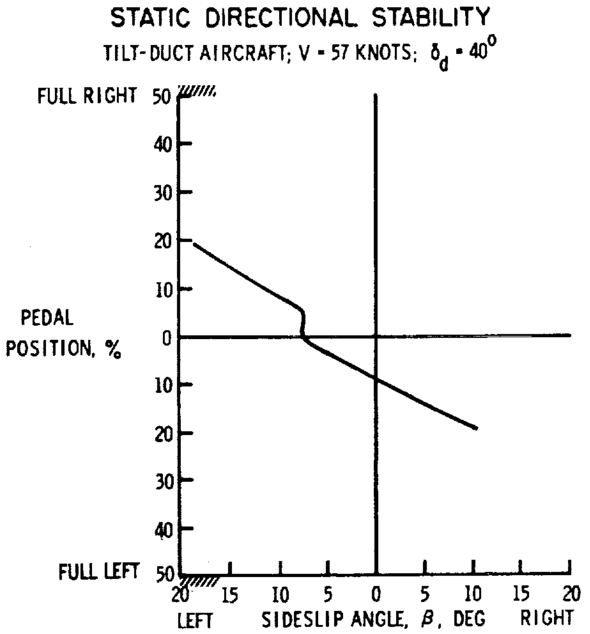


Figure 19

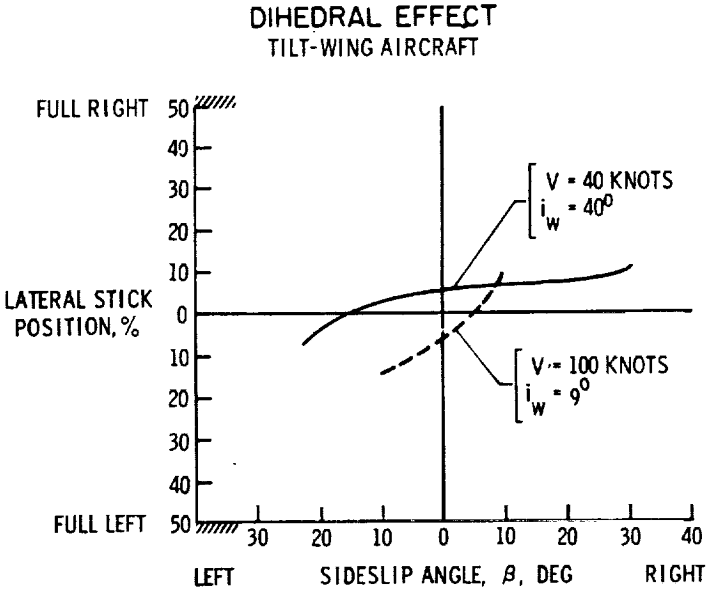


Figure 20

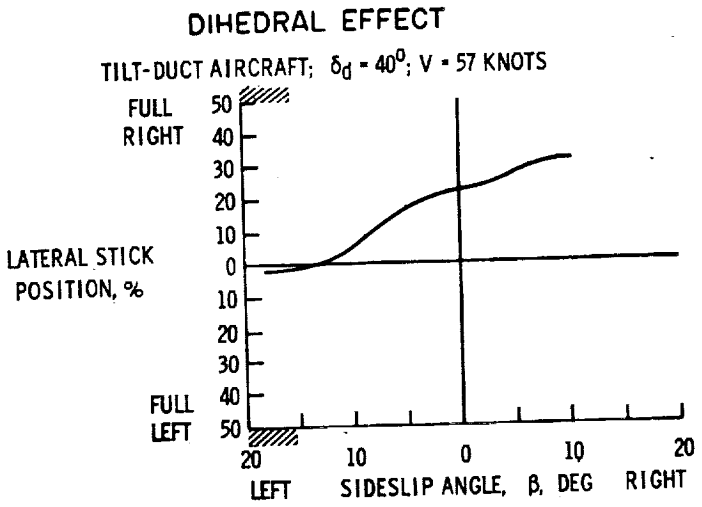


Figure 21

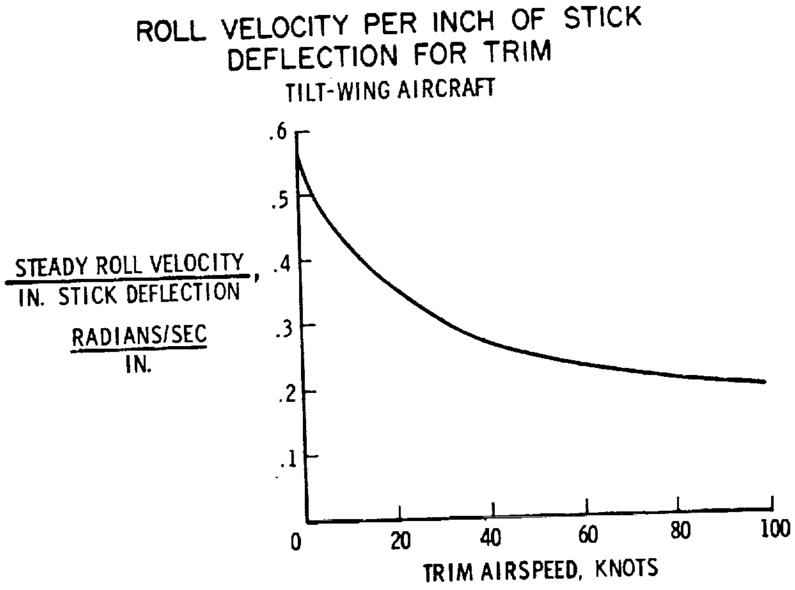
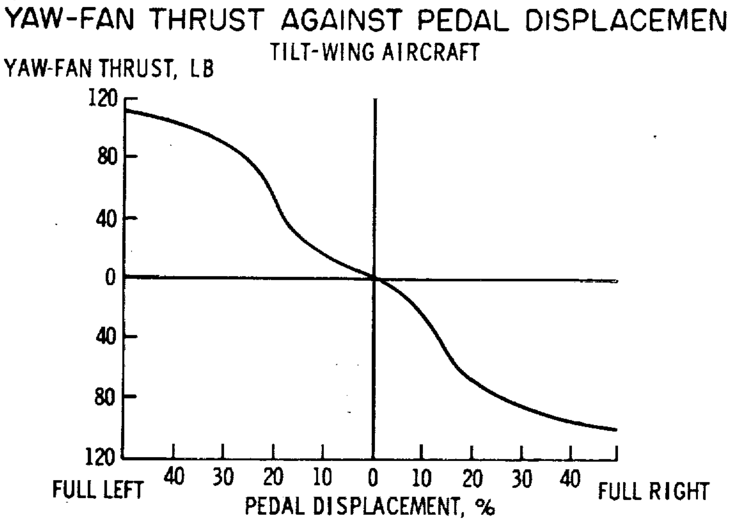


Figure 22



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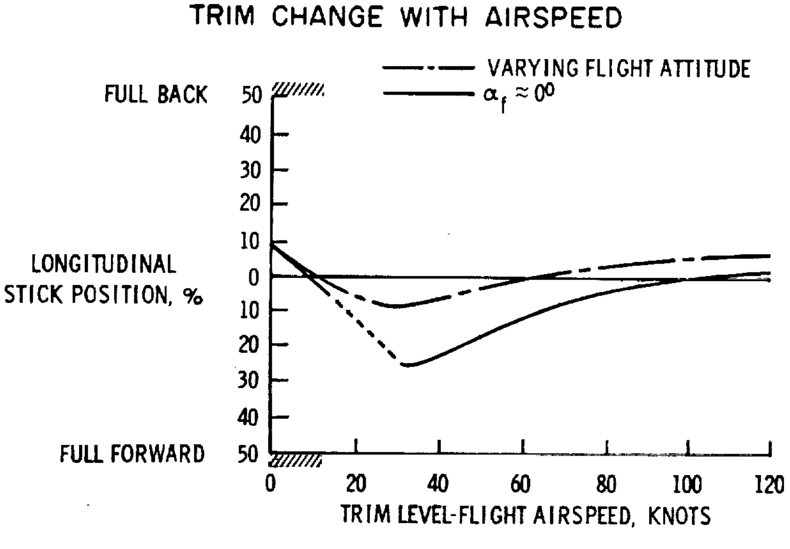

Figure 24

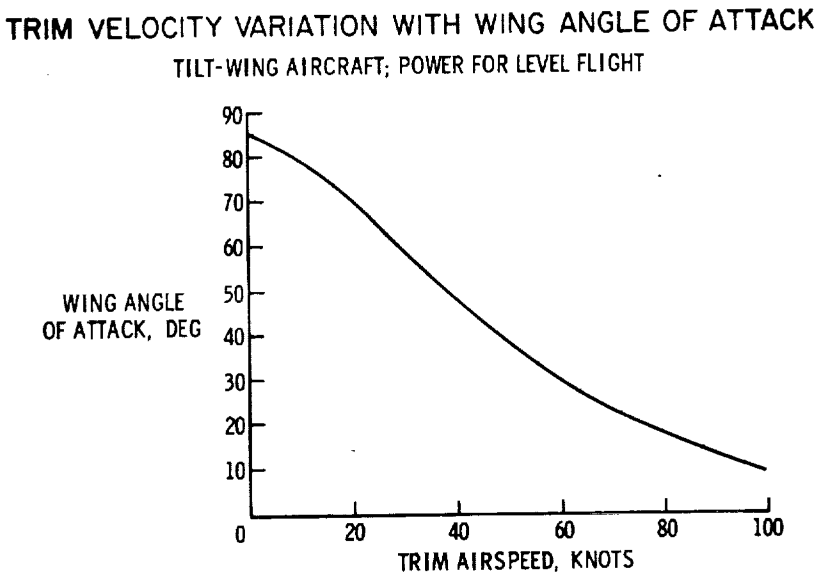

Figure 25

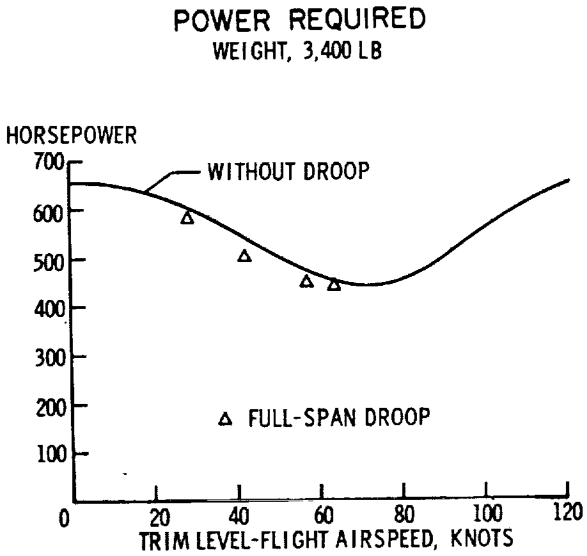

Figure 26