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AERODYNAMIC CHARACTERISTICS OF PROPELLER-DRIVEN VTOL AIRCRAFT

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SUMMARY

This paper discusses the two major configurations that are usually considered for achieving VTOL while keeping the fuselage essentially horizontal - that is, the tilt-wing and the deflected-slipstream configurations.

Because of the high turning losses incurred by deflected-slipstream configurations in hovering and because of the wing-stalling problem of the pure tilt-wing configurations during the transition, it appears that a combination of the two principles should be used. This tilt-wing and flap configuration should make use of a programed extensible-chord slotted flap together with a leading-edge high-lift device in order to avoid the performance and handling qualities problems associated with wing stalling during the transition while keeping the wing area as low as possible for efficiency in cruising flight.

INTRODUCTION

The purpose of this paper is to show some of the basic performance and aerodynamic characteristics of propeller-driven VTOL aircraft, to discuss the major problems involved, and to indicate solutions wherever possible. Under discussion are the two major propeller configurations that are usually considered for achieving VTOL while keeping the fuselage essentially horizontal - that is, the tilt-wing and the deflected-slipstream configurations. Only the hovering and transition ranges of flight are treated herein because in cruising flight these aircraft are essentially conventional propeller-driven airplanes with normal aerodynamic characteristics.

SYMBOLS

C_L	lift coefficient, Lift/qS
c	wing chord, ft
D	propeller diameter, ft
M_α	pitching moment due to change in angle of attack, ft-lb/deg
q	dynamic pressure, $\frac{1}{2}\rho V^2$, lb/cu ft
q_t	dynamic pressure at the tail, lb/cu ft
S	wing area, sq ft
V	airspeed, ft/sec
α	angle of attack, deg
ϵ	downwash angle, deg
ρ	air density, slugs/cu ft

DISCUSSION

Hovering

One of the major aerodynamic problems in hovering is illustrated in figure 1. In this figure the hovering effectiveness of deflected-slipstream configurations is shown in terms of the ratio of lift available for hovering to the propeller thrust plotted against the angle of slipstream deflection. For the deflected-slipstream configurations where large flaps are utilized to turn the slipstream through appreciable angles, there is a considerable loss in lift. The two curves in figure 1 are typical of the results obtained from tests on deflected-slipstream configurations. (See ref. 1.) The dashed curve, for a configuration employing two propellers, shows that only moderate angles of slipstream deflection can be achieved without incurring large losses. The solid curve, for a configuration with four propellers, shows that the turning losses are somewhat smaller. The effect resulting from the use of either two or four propellers is somewhat like an aspect-ratio effect - that is, the tip losses are greater for the two-propeller arrangement. These data are for conditions out of ground effect; the effect of the ground on these and other VTOL configurations is discussed in reference 2. A tilt-wing configuration exhibits essentially no loss in lift because the propellers are tilted instead of the slipstream being deflected. These are the only points to be made in connection with the performance in the hovering flight range and the rest of the paper considers the characteristics in the transition range of flight.

Aerodynamic Factors Affecting Performance in Transition

In figure 2 is indicated the power required during transition for the tilt-wing and the deflected-slipstream configurations. These data and all other power-required data presented herein have been calculated for an assumed aircraft gross weight of 3,600 pounds. The dashed curve labeled "Ideal" shows the calculated induced power required with an assumed, uniform span loading without wing stalling, as discussed in reference 3. For hovering flight the deflected-slipstream configuration required considerably more power than that indicated by the ideal curve because of the losses incurred in turning; however, the power required for this configuration rapidly approaches that of the ideal curve as the speed increases. On the other hand, the tilt-wing configuration requires no more power than the ideal in hovering but rapidly diverges with forward speed and requires considerably more power during the transition than either the deflected-slipstream configuration or that indicated by the ideal curve. The excess power required during transition is caused by wing stalling. This wing stalling is a problem not only because of its effect on power required which is reflected in poor overload STOL performance (ref. 4) but also because of its large effect on handling qualities as is brought out in reference 5.

In order to understand this wing stalling, figure 3 is presented and shows in schematic form the wing angle of attack during transition flight for the level-flight, climb, and descent conditions. For the level-flight condition, a horizontal vector represents the forward-flight velocity and another vector represents the incremental velocity added by the propeller. These two vectors give the resultant velocity that is experienced by the wing. The angle of this resultant vector to the wing is then the angle of attack that the wing experiences. Of course, changes in disk loading change the incremental velocity added by the propellers. A higher disk loading gives a higher slipstream velocity and therefore reduces the wing angle of attack. Also, the portions of the wing that are not in the propeller slipstream experience a very high angle of attack under these conditions and should be kept to a minimum. Figure 3 also shows the effects of climb and descent on the wing angle of attack. The conditions shown are for maintaining constant forward velocity and wing attitude with respect to the ground. For the descent condition, the power is reduced which, in turn, reduces the slipstream velocity increment added by the propeller, and the direction of the free-stream velocity is also changed. As a result of these two changes, there is a considerable increase in the angle of attack of the wing in descent. For the climb condition, the velocity changes are in the opposite direction and, therefore, the angle of attack is reduced.

Figure 4 shows a typical variation of angle of attack of the wing
with forward speed for the descent, level-flight, and climb conditions.
The dashed line shows the approximate stall angle of attack of a repre- L
sentative airfoil. Figure 4 shows that, if a wing was about at the 1
stall angle in level flight, it would stall in descent over a wider 4
range of speeds but would be unstalled in climbing flight. It also 1
appears from this figure that stalling might not occur in level flight, 1
except over a small range of speeds. However, the stall picture is not
as clear cut as indicated by this figure. This representation is that
which would be obtained with counterrotating propellers where there is
no rotation in the slipstream. For the single-rotation propeller, the
slipstream rotation complicates the problem, as indicated in figure 5.

Figure 5 shows the variation of wing section angle of attack with speed. The curve for level flight with no rotation is reproduced from figure 4. Actually, as shown by the sketch at the bottom of figure 5, the slipstream rotation causes an increase in angle of attack on one side of the propeller disk and a decrease on the other side. The magnitude of the change in angle of attack for the case indicated by the sketch is shown by the other two curves. The top curve shows that the wing sections experiencing upward flow from the slipstream are stalled for practically the entire transition range, whereas the bottom curve indicates an unstalled condition, at least for level flight, for the wing sections experiencing downward flow from the slipstream.

Figures 2 to 5 have presented the problem of wing stalling on tilt-wing configurations during the transition range of flight. Ways to reduce this problem are now considered. The approaches to use are indicated in a qualitative way in figure 6. This figure shows lift curves for a wing with high-lift devices. If the wing is near stall, one means of avoiding it is to increase the stall angle of the wing by the use of a slat or some other leading-edge device. Another means of avoiding stalling is to use a flap which, for the same lift, reduces the wing angle of attack to get away from the stall region. Of course, both the flap and slat can be used to get double benefit. Another way, which is not shown directly in figure 6, is to use more chord and therefore more wing area. With more wing area the required lift can be produced with a lower lift coefficient which again moves the wing farther from the stall region.

Figures 7 to 9 show some experimental data demonstrating the use of these cures. Figures 7 and 8 are based on the data contained in reference 6 and figure 9 is based on the data in reference 7.

Figure 7 shows the effect of wing chord on power required as a function of speed for wings having chord-diameter ratios of 0.33, 0.50, and 0.75. This might also be considered the effect of wing area - that is, the area immersed in the propeller slipstream. Figure 7 shows very readily that as the wing chord is increased, the power required is markedly reduced.

Figure 8 shows the effect of a slat on power required for the three wings of different chord-diameter ratios used in figure 7. For each wing curves are shown for no slat, slat on, and the ideal case. Again, it is evident that the slat made a significant improvement in the power required and presumably in the wing stalling.

The effect of flaps on the power required is shown in figure 9 for the pure tilt-wing configuration and for the same wing with a 40-percent extensible-chord slotted flap deflected 50° throughout the range of flight. The use of this flap gives a power-required curve that very closely approaches the ideal curve. With the flap deflected 50°, however, a considerable increase in power is required for hovering. In actual practice, then, it would seem more logical to program the movement of the flap so that the flap would be at 0° for hovering and cruise but would be deflected for intermediate angles of tilt through the speed range.

From figures 7 to 9 it can be seen that the use of either adequate wing chord, slats, or flaps tends to reduce the effect of wing stalling during the transition range of flight. The question, then, is which approach and how much of each to use. For example, for the case illustrated in figure 9, the use of a large wing chord and a flap ($c/D = 0.84$ with flap extended) results in performance that probably cannot be improved by the addition of a slat. In actual practice, however, the wing of a propeller-driven airplane tends to be overly large for maximum performance in cruising flight and therefore it is of interest to keep the wing area or wing chord as small as possible for cruising flight. For this reason, it appears that flaps and slats should be used to their fullest extent during transition and the chord should be made just large enough to avoid serious stalling. Also, it seems logical that a flap that extends the chord of the wing when deflected should be used in order to keep the area of the basic wing to a minimum for cruising flight.

Aerodynamic Factors Affecting Stability and Trim

In figure 10 the pitching moment for the steady-flight condition throughout the transition range is shown for the tilt-wing and deflected-slipstream configurations. The pitching moment is presented as the amount of trim force required at the tail in percent of gross weight. Basically the tilt-wing configuration tends to give a nose-up pitching moment during transition because of a large nose-up moment produced by the propeller itself. The deflected-slipstream configuration has nose-down pitching moments because of the diving moments of the flaps about a center of gravity located at the quarter-chord station that was used in this figure. The magnitude of these pitching moments for both configurations is such that large trim forces would be required at the tail at airspeeds that are so low that the horizontal tail could not be expected to have an appreciable effect. These moments would therefore impose a severe additional requirement on the hovering controls which, from other considerations, would be required to produce a force at the tail of about ±5 percent of the gross weight.

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The two curves in figure 10 indicate that for a combination tilt-wing and deflected-slipstream configuration, the flaps could be programed to give effectively zero pitching moment throughout the whole transition range. This point has been checked out in wind-tunnel tests and it was found that the pitching moments can be trimmed out with a relatively modest amount of flap or by simply a single slotted or extensible-chord slotted flap. These tests also showed that for this combination tilt-wing and flap configuration the program of flap deflection required to eliminate the pitching moment was also very effective in minimizing wing stalling and in achieving a desirable low power-required curve.

Figure 11 indicates the characteristics of the air flow at the tail for an arrangement shown by the sketch. The data, however, are reasonably representative of the flow for either the tilt-wing, deflected-slipstream, or combination tilt-wing and flap configuration. The top curve shows that there is a considerable range of speeds where the dynamic pressure at the tail q_t is so low that the horizontal tail would not have any effectiveness and the pilot would have to rely entirely on the hovering controls. The middle curve shows that there is a large variation of downwash angle ϵ over the speed range and, therefore, a variable-incidence horizontal tail would probably have to be installed to keep the tail from producing undesirably large nose-up pitching moments during the latter part of the transition. The bottom curve shows the variation of the downwash factor $\left(1 - \frac{d\epsilon}{d\alpha}\right)$, a stability factor which influences the effectiveness of the tail for producing static longitudinal stability. Small values indicate that the tail will be ineffective, whereas large values indicate that the tail will be very effective.

From the bottom and top curves of figure 11, it is evident that at low speed, not only is the force produced small because of low q_t but the force produced is not very effective for static stability because of the unfavorable downwash characteristics.

In figure 12 the variation of static longitudinal stability - that is, stability of attitude - in the transition range is presented for seven different configurations that have been tested: two deflected-slipstream, three tilt-wing, and two combination tilt-wing and flap configurations. The data show that all these configurations tend to be unstable at low speed and become stable at higher forward speeds, as expected from the results of the data in figure 11.

The degree of static longitudinal stability is indicated in figure 12 in dimensional terms (ft-lb/deg) since ordinary nondimensional coefficients based on forward speed lose their significance as the speed approaches zero. The data from these different configurations, both full scale and model, were scaled to represent an aircraft weighing about 3,600 pounds in order to show them in the same plot. The actual numbers are not important. The significant point is that the trend is about the same for all the widely different configurations and all become stable at about the same speed. The instability in the low speed range has not seemed to bother the pilots flying the test beds, probably because of the low speeds involved. Also, it should be remembered that the static stability parameter M_{α} is only one of the factors affecting longitudinal flight characteristics.

Control

The amount of control required for propeller-driven VTOL aircraft is discussed in reference 8 but the point to be discussed in this paper is the means of obtaining this control in hovering and low-speed flight with propeller-driven configurations. Roll control and yaw control are fairly straightforward. It is evident that the variable pitch propeller controls that will already be on the airplane can be used for roll control. It also seems likely that the flaps or ailerons, which would be in the propeller slipstream, can be used for yaw control, although this idea has been only partially checked out by research. Pitch control, however, is not so straightforward and depends to a great extent on the wing position, as is indicated in figure 13.

Shown in figure 13 are three possible wing arrangements: a low wing with the pivot forward on the wing chord and two high wings - one with a forward pivot, such as that used on the tilt-wing test beds, and one with a rear pivot. Concerning the low wing arrangement, it can be seen that the trailing-edge flaps have an appreciable moment arm from the aircraft center of gravity which gives the possibility of obtaining pitch control from these flaps in hovering and low-speed flight. However, with the high wing arrangements, the flap load is so close to the center of gravity that the flaps are ineffective for pitch control and some other means of control must be used. One method is the installation of cyclic pitch control and flapping blades. Another and perhaps a simpler method would be the use of an auxiliary control such as a tail rotor, as indicated in the sketches of figure 13. Of course, aerodynamics is not the only consideration in selecting a wing arrangement. For example, two other considerations that are obvious from the sketches are that the low wing gives a high fuselage which results in loading problems (particularly for military applications) and that the high wing with forward pivot gives very little structural carry-through in the center of the wing since most of the wing chord has to pivot beside the fuselage.

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CONCLUDING REMARKS 1
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Because of the high turning losses incurred by deflected-slipstream configurations in hovering and because of the wing-stalling problem of the pure tilt-wing configuration during the transition, it appears that for a propeller-driven VTOL aircraft, a combination of the two principles should be used. This tilt-wing and flap configuration should make use of a large extensible-chord slotted flap together with a leading-edge high-lift device in order to avoid the performance and handling qualities problems associated with wing stalling during the transition while keeping the wing area as low as possible for efficiency in cruising flight. 1

The flap should be programed so that it is at zero deflection with 90° wing incidence for high hovering efficiency and is deflected only in the transition range of flight. The actual flap programing can be chosen to give both minimum pitch trim through the transition range and near optimum results from the power-required and wing-stalling considerations. Since this arrangement results in a low power-required curve, it would also have good STOL performance.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., November 17, 1960.

REFERENCES

1. Kuhn, Richard E.: Semiempirical Procedure for Estimating Lift and Drag Characteristics of Propeller-Wing-Flap Configurations for Vertical- and Short-Take-Off-and-Landing Airplanes. NASA MEMO 1-16-59L, 1959.

2. Schade, Robert O.: Ground Interference Effects. NASA TN D-727, 1961.

3. Kuhn, Richard E.: Review of Basic Principles of V/STOL Aerodynamics. NASA TN D-733, 1961.

4. Kuhn, Richard E.: Take-Off and Landing Distance and Power Requirements of Propeller-Driven STOL Airplanes. Preprint No. 690, S.M.F. Pub. Fund Preprint, Inst. Aero. Sci., Inc., Jan. 1957.

5. Reeder, John P.: Handling Qualities Experience With Several VTOL Research Aircraft. NASA TN D-735, 1961.

6. Taylor, Robert T.: Wind-Tunnel Investigation of Effect of Ratio of Wing Chord to Propeller Diameter With Addition of Slats on the Aerodynamic Characteristics of Tilt-Wing VTOL Configurations in the Transition Speed Range. NASA TN D-17, 1959.

7. Kuhn, Richard E., and Hayes, William C., Jr.: Wind-Tunnel Investigation of Longitudinal Aerodynamic Characteristics of Three Propeller-Driven VTOL Configurations in the Transition Speed Range, Including Effects of Ground Proximity. NASA TN D-55, 1960.

8. Anderson, Seth B.: An Examination of Handling Qualities Criteria for V/STOL Aircraft. NASA TN D-331, 1960.

HOVERING EFFECTIVENESS OF DEFLECTED-SLIPSTREAM CONFIGURATIONS

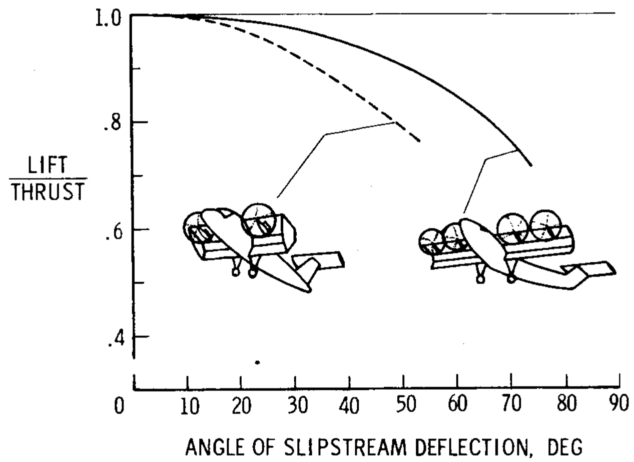

Figure 1

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POWER REQUIRED DURING TRANSITION

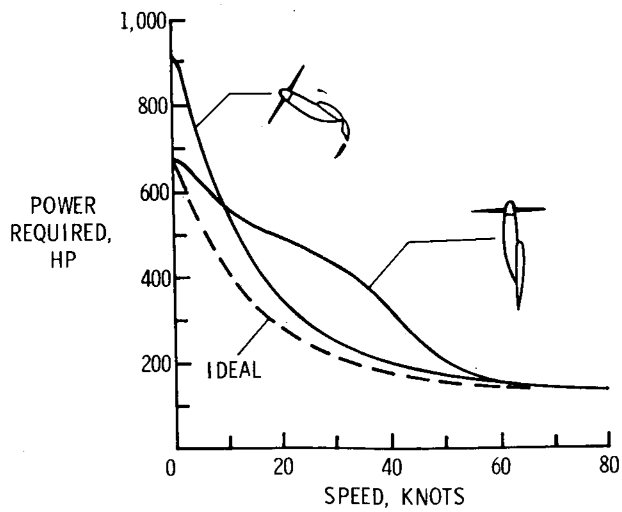

Figure 2

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WING ANGLE OF ATTACK DURING TRANSITION FLIGHT

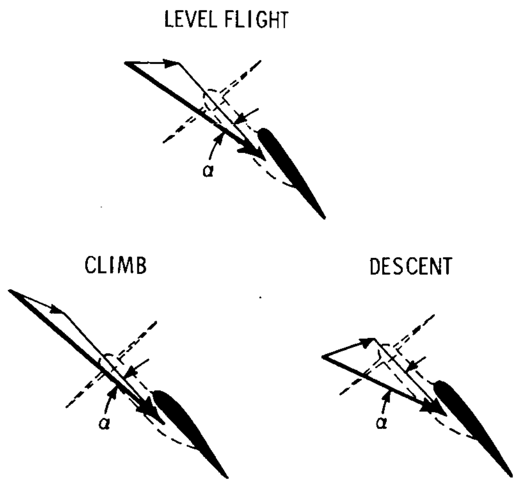

Figure 3

TYPICAL VARIATION OF ANGLE OF ATTACK WITH SPEED

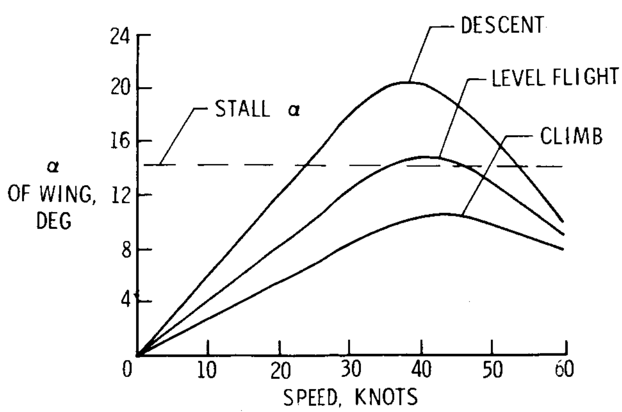

Figure 4

EFFECT OF SLIPSTREAM ROTATION ON ANGLE OF ATTACK

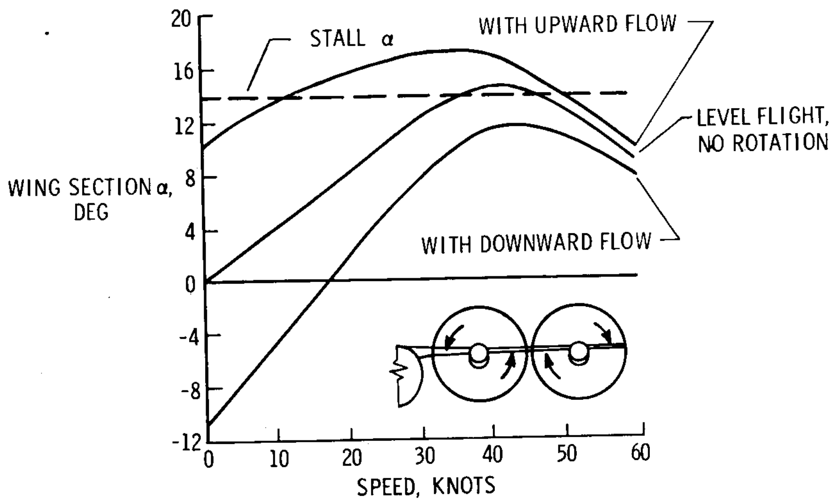

Figure 5

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CHANGES IN LIFT CURVES CAUSED BY HIGH-LIFT DEVICES

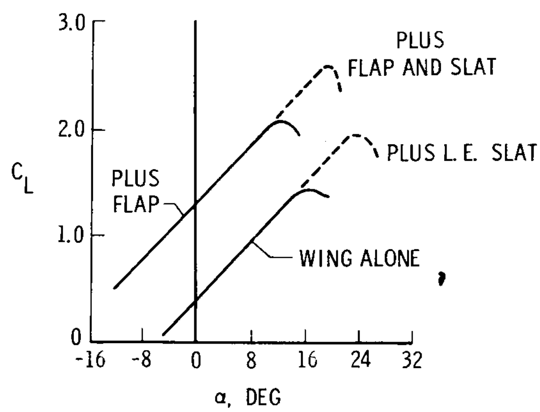

Figure 6

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EFFECT OF WING CHORD

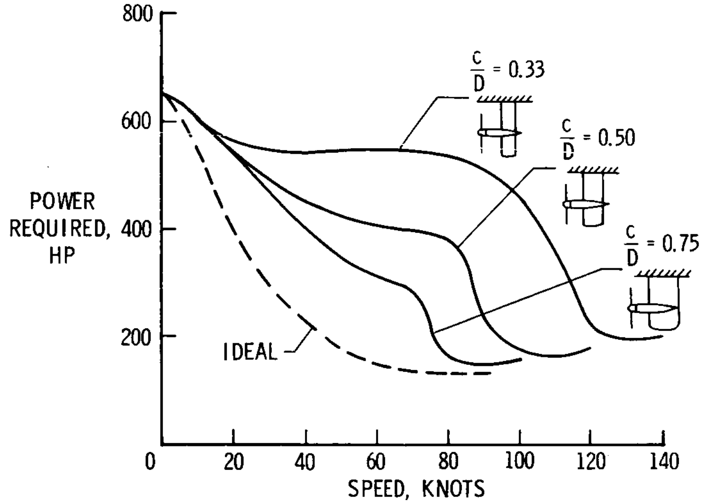

Figure 7

EFFECT OF SLATS

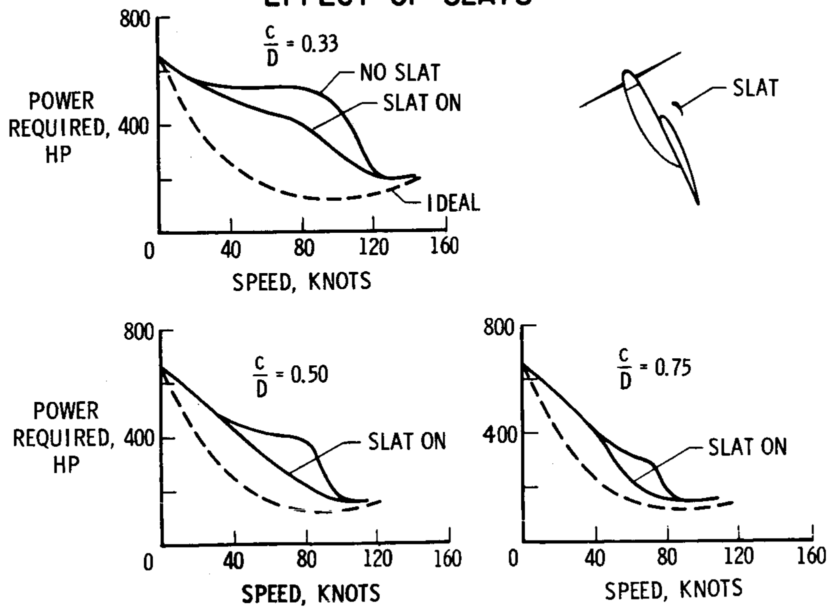

Figure 8

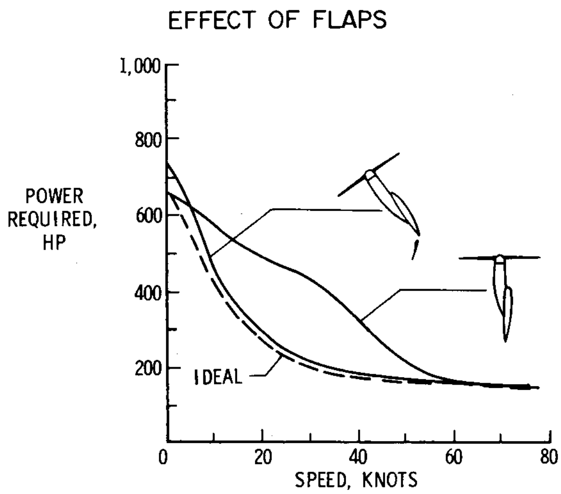

Figure 9

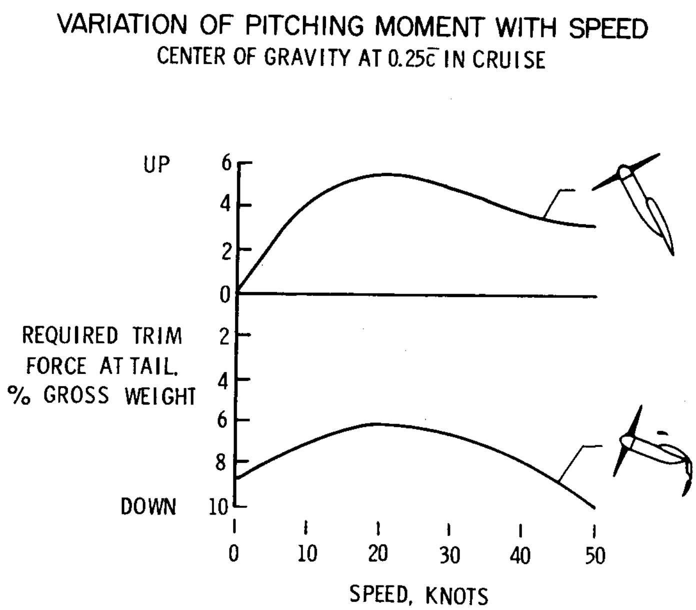

Figure 10

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CHARACTERISTICS OF THE AIRFLOW AT TAIL

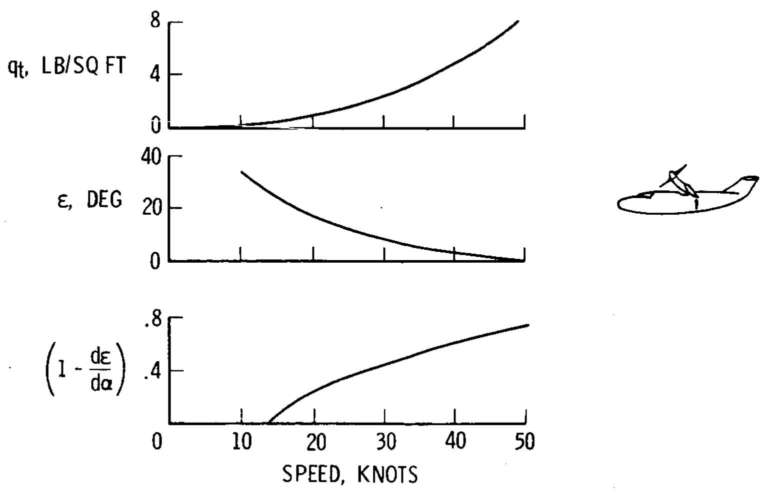

Figure 11

STATIC LONGITUDINAL STABILITY

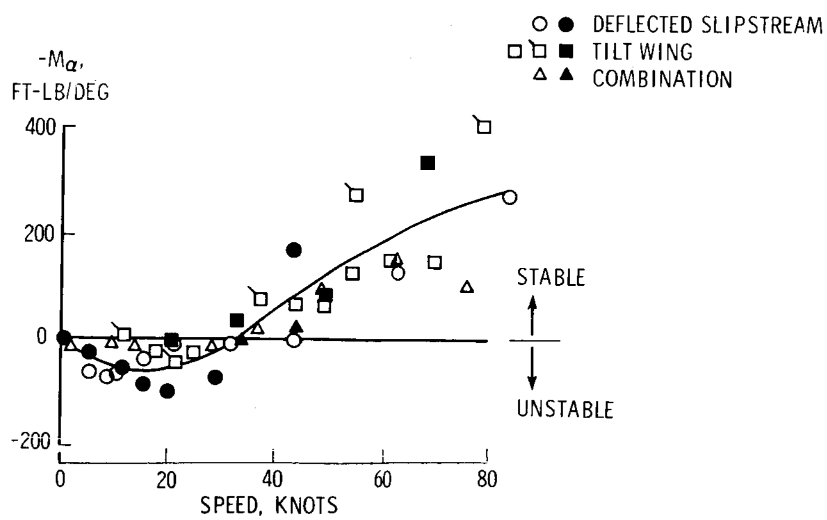

Figure 12

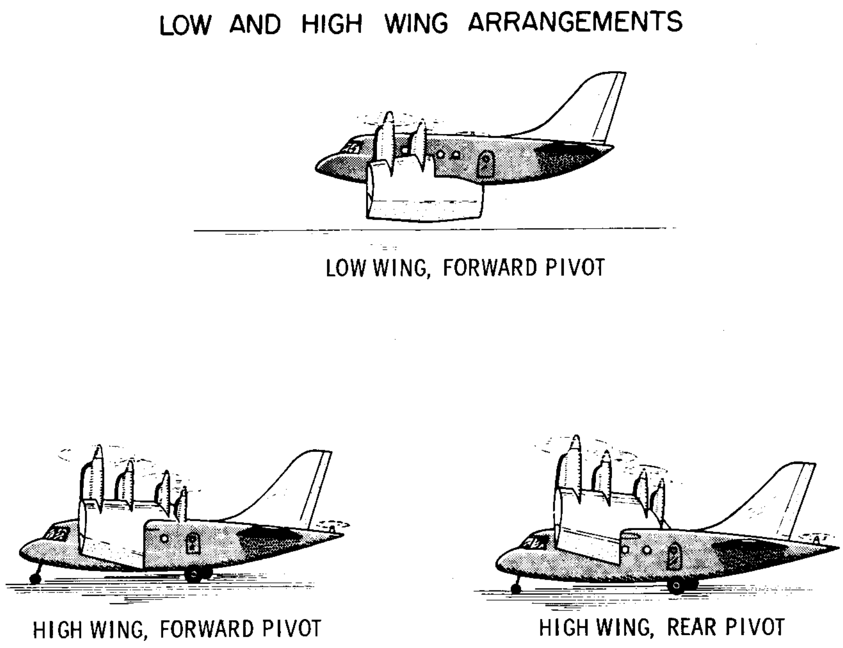

Figure 13

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