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HANDLING QUALITIES EXPERIENCE WITH SEVERAL VTOL RESEARCH AIRCRAFT

By John P. Reeder

Langley Research Center

SUMMARY

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All of the VTOL research aircraft discussed in this paper have successfully demonstrated conversion from hovering to airplane flight and vice versa. However, control about one or more axes of these aircraft has been inadequate in hovering flight. Furthermore, ground interference effects have been severe in some cases and have accentuated the inadequacy of control in hovering and very low speed flight.

Stalling of wing surfaces has resulted in limitation in slowdown and descending flight, particularly for the tilt-wing aircraft, which is a very rudimentary type. Minor modifications to the wing leading edge in this case have, however, produced surprisingly large and encouraging reductions in adverse stall effects.

Height control in hovering and in low-speed flight has proved to be a problem for the aircraft not having direct control of the pitch of the rotors. The other systems have shown undesirable time lags in development of a thrust change.

INTRODUCTION

The flight experience to be discussed has been acquired on VTOL research aircraft having four different types of rotor systems which provide vertical thrust for hovering and propulsion for forward flight. The aircraft are the Bell XV-3 with tilting rotors and a fixed wing, the Vertol VZ-2 with a tilting wing and flapping rotors, the Curtiss-Wright X-100 with tilting propellers and a very small fixed wing, and the Doak VZ-4 with tilting, ducted fans at the tips of a fixed wing.

Operation of the test-bed aircraft has, in general, been limited to light wind conditions. Also, all the aircraft have been power limited so that hovering flights have been considerably restricted. They have all demonstrated conversions from hovering to airplane flight and vice versa. The VZ-2 is the only one of the aircraft that has stability augmentation systems. These provide damping about the roll and pitch axes. This paper discusses the aircraft without the system functioning.

Only significant areas of the handling qualities of the test beds pertinent to improved design of the next generation of VTOL aircraft are discussed in this paper.

STABILITY AND CONTROL

Photographs of the four VTOL research aircraft under discussion are presented in figures 1 to 4. The significant areas of the basic stability and control characteristics of these aircraft are summarized in table I. The presence of a letter in the table indicates which aircraft has a significant characteristic in the particular phase of flight indicated. This paper will discuss these characteristics in the various phases of flight.

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Hovering

Figure 5 is a summary chart of hovering stability and control characteristics for the VTOL research aircraft. The parameters plotted, the ratio of angular velocity damping to inertia of the aircraft and angular acceleration capability of the control per inch displacement, were found to be important handling-qualities criteria in the evaluation of helicopters. The boundaries of desirable and unacceptable characteristics shown were obtained from flight tests with a variable-stability helicopter during hovering maneuvers and low-speed, precision, instrument-flight tasks. It is felt that the boundaries are applicable to the next generation of VTOL aircraft in lieu of better information.

The lateral or roll control of the VZ-4 aircraft in hovering is obtained by means of controllable inlet guide vanes. This control in its present stage has proved to be very inadequate, as indicated in figure 5. The other aircraft have tended to be too responsive to lateral control, but this is not considered a basic problem since the control power can be reduced.

Longitudinal stability and control of the VZ-2 aircraft in hovering without the pitch-rate damper has caused difficulty for the unindoctrinated pilot. The basic aircraft has exhibited very low damping in pitch in hovering flight with no wind. Also, the longitudinal control is nonlinear and weak, and the control system does not permit exact positioning of the control for trim. When first trying to hover without the pitch damper, using hand and wrist motions for controlling, the pilot felt he was out of phase with an expanding oscillation. He quickly had to convert to an arm and shoulder technique with which he could put in sufficient control at a higher rate. No further difficulty was experienced after this except that continuous controlling was necessary.

All the aircraft have deficiencies about the yaw axis in hovering. As shown in figure 5, they all show little damping and very weak control about this axis. However, the yaw axis is of least concern in hovering, particularly for a test bed, inasmuch as little hazard results from the lack of control. Of course, for an operational vehicle intended to perform precision maneuvers under all weather conditions, the yaw control requirements will have to be considerably greater than for these aircraft.

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Experience has indicated that the length of time required in hovering prior to a landing is a direct function of the controllability of the aircraft; that is, the poorer the controllability, the greater the time required.

Accelerating Conversion

The power used in an accelerating conversion is more than that required for level flight. In the test-bed operation, it has most often been the maximum power available. During maximum-power operation of the VZ-2 aircraft in climb at a wing incidence angle of about 20°, an unstable Dutch roll oscillation with a period of about 4 seconds has been encountered. Although controllable, this oscillation was of concern to the pilot. The oscillation is thought to be due to the destabilizing effects of having the principal axis of inertia nose down with respect to the flight path. It is felt that such oscillations can be readily damped with simple rate stability augmentation systems.

Other problems encountered in accelerating conversions have been more critical in the decelerating conversion or descent phase and are discussed subsequently.

Cruise

In the cruise condition, which is considered to be airplane flight, the XV-3 aircraft has a poorly damped short-period pitching oscillation which becomes more poorly damped as rotational speed of the rotors is reduced. In rough air, rather large yaw disturbances have been observed to couple with the pitch oscillation to produce an annoying circular motion of the nose of the aircraft.

A short-period longitudinal oscillation is also evident in the VZ-2 aircraft, but to a lesser extent. In this case little undesirable behavior results, but the damping is less than desirable. During one landing as an airplane, a gentle flare was started at 95 knots, but an uncontrollable tendency to balloon was immediately apparent. The approach was successfully continued to landing by using power alone as height control. The ballooning tendency might well have been a result of the poor damping in pitch.

Decelerating Conversion and Descent

During conversion, the X-100 aircraft develops a nose-up change in trim at high nacelle angles in slow forward flight due to a forward shift of resultant force on the propellers. The largest forward stick displacement to offset these moments is required at about 20 to 30 knots. At powers used in flight, however, a margin of control remained throughout this region of flight.

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The VZ-4 aircraft develops a large nose-up trim change due to the ducts at duct angles of the order of 60°. In the original duct configuration, the moments were large enough to make full forward stick control necessary at about 20 to 25 knots in a level flight slowdown to hovering flight. Also, the trimmable stabilizer had to be set for full nose-down trim and the airplane still had to be allowed to pitch up to more than 15° angle of attack. The exit guide vanes, which are programed to offset the duct moments, now make it possible to traverse this region at a constant attitude with some margin of elevator control remaining.

In the case of these two aircraft (the X-100 and the VZ-4), the pitching-moment changes appear to the pilot as instabilities with respect to speed, which will be very undesirable during landing approaches, particularly under instrument conditions.

During all flight phases, the VZ-2 aircraft has static directional, or weathercock, instability over a range of left sideslip angles. In the cruise phase, this is probably due to the low dynamic pressure at the tail because of the high drag configuration. However, at higher wing incidence angles, strong cross flows may very well be present which may require research to establish a cure. Figure 6 shows pedal position plotted against sideslip angle from directional stability tests at two wing incidence angles. For the cruise condition (wing incidence angle of 9°), the instability exists over a much smaller range than at a wing incidence angle i_w of 40°. However, the pilot's impression is that the instability is worse at a velocity V of 100 knots than at a velocity of 40 knots because the angular acceleration is higher as divergence begins, corresponding to the higher dynamic pressure. At the lower speed, however, considerable use of control is required because of the reduced effectiveness of the control.

Landing

The limitations due to stalling that occur with the VZ-2 aircraft and, to some extent, with the VZ-4 aircraft during descent are discussed subsequently in this paper. However, one limitation of control for the VZ-2 aircraft exists during the last stages of a slow descent and landing as an STOL aircraft. At less than 30 knots, the directional control power is insufficient to correct adequately for even light crosswinds or gust disturbances. Although the longitudinal control also becomes too weak to adjust the attitude for a three-point landing within the ground-effect region below 30 knots, this weakness constitutes less of a problem than the directional one because the aircraft can be readily landed on the wheels.

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FACTORS THAT INFLUENCE HANDLING QUALITIES

Some very important factors that influence the handling qualities of the VTOL research aircraft and emphasize their need for more adequate control are presented in table II. Table II is similar to table I with the phases of flight indicated as before. The factors to be discussed are tabulated on the left with the letters B, C, D, and V indicating which aircraft seem to have significant characteristics in the various phases of flight.

Ground-Downwash Interference Disturbances

Hovering.- Near the ground, the VTOL aircraft are subjected to severe recirculation airflows. The details of this problem are discussed in reference 1. Suffice it to say that the aircraft are greatly disturbed in this interference region. It has been difficult to pinpoint a height above the ground at which the disturbances cease, but it has been about 10 to 15 feet in the case of the test-bed aircraft. Above this height the aircraft are all fairly steady and free of vibration.

The XV-3 and X-100 aircraft suffer from erratic wing dropping and yawing in this interference region, the effect being stronger for the X-100 aircraft. Noticeably large lateral control displacements are required to offset the lateral disturbances, particularly for the X-100 aircraft. This may be significant inasmuch as these aircraft otherwise have powerful roll control. In yaw the aircraft cannot be controlled within 10° to 20° of a desired heading because of the very weak control, but this does not necessarily create a hazard in hovering flight.

The VZ-2 aircraft has not shown roll disturbances in hovering of which the pilot is particularly aware. However, it does suffer heavy buffeting and more abrupt and larger yaw disturbances than the XV-3 or X-100 aircraft. Translatory accelerations of the aircraft are also apparent. The yaw disturbances cannot always be controlled in this case either.

The VZ-4 aircraft does not suffer from buffeting, and the disturbances it suffers are not as abrupt as for the others. However, if lifted clear of the ground several feet, uncontrollable yawing and persistent lateral upsetting tendencies have been encountered. With the weak yaw control and, particularly, the weak roll control described previously, the unindoctrinated pilot may find himself unable to control the aircraft.

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Accelerating conversion.- The effects of ground interference are intensified as the aircraft advances into the disturbances which it is forcing out ahead of itself. The speed range at which at least three of the aircraft encounter the most disturbance is from about 15 to 20 knots. Beyond this speed range the downwash field shifts aft, as it is for an airplane, and disturbances cease.

The disturbances in both roll and yaw for the XV-3 and X-100 aircraft are considerably greater under these conditions than for hovering, and it is very difficult to maintain lateral control and a heading in the direction of the desired track while advancing through this region. Yaw disturbances are greatly intensified for the VZ-2 aircraft also, and it is sometimes impossible to maintain heading closer than 20° to the track. Again, though, roll disturbances have not been particularly apparent to the pilot in this aircraft.

In none of these aircraft have appreciable pitch disturbances been noted by the pilot.

It is apparent that the aircraft should either climb through the critical altitude region as quickly as possible, power permitting, or operate as an STOL type and take off at a speed above that at which the disturbances disappear. It is not possible to avoid the most critical disturbance speed altogether by taking off vertically, however, because winds of about 15 knots will create the same situation as forward translation with calm winds.

In the final stages of a landing approach to a near vertical landing, the same behavior patterns just described happen in reverse. This behavior becomes more hazardous for the landing than for the take-off and acceleration phase.

Ground Effect on Power Required

The X-100 aircraft has exaggerated ground effect on power required up to heights of about 20 feet, whereas the VZ-2 aircraft, which has a similar rotor configuration, has essentially none. The X-100 aircraft has a covered fuselage with a flat bottom and rounded corners. The strong ground effect on lift probably comes largely from impingement of the recirculating flows on the bottom of the fuselage.

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It has been noted that the X-100 aircraft settles rapidly toward the ground when upset in bank or pitch attitude in the ground-effect region. Also, at a speed of 15 or 20 knots while in a level attitude and after accelerating through the region of most intense disturbances, the aircraft rather suddenly settles toward the ground. This unusual settling behavior may be caused by a shift in the area of impingement of the upward flow under the aircraft due either to an attitude or a velocity change, thus resulting in a loss of lift on the fuselage. From the pilot's standpoint, the settling and the lateral upsetting moments that may occur are very undesirable. The implications are that in hovering in operational wind conditions or in traversing the interference flow region, the behavior of VTOL aircraft may be very unpredictable, depending on fuselage design and the sensitivity of downwash patterns to attitude or speed changes.

Adverse Stall Effects

The most critical regions of operation for some V/STOL aircraft are the decelerating conversion and descent. Stalling of lifting surfaces under these conditions is probable, leading to buffeting, uncontrolled-for motions, and general difficulty in handling the aircraft. The X-100 aircraft is notably free of disturbances and airframe roughness in these flight phases, at least away from the ground.

The VZ-2, a rudimentary tilt-wing aircraft, had serious stall-imposed limitations in its original wing configuration as shown in figure 7. The boundary shown on the right with heavy crosshatching is that for stall onset. At wing incidence angles between approximately 25° and 35°, enough power to climb had to be used if wing drop, heavy buffeting, and large yaw disturbances were to be avoided. Deceleration in level flight through about the same incidence range at rates great enough to require reduction of power to less than 350 horsepower had to be avoided for the same reasons. At higher wing incidence angles such as 40°, the stalling became symmetrical, and buffeting intensity was reduced because of lower speed so that a reasonable rate of descent could be attained for approach to a landing in smooth air. In rough air, the usable rates of descent were considerably reduced. Actually, the buffeting and poor directional behavior in these descent conditions were tolerated only because lateral and longitudinal control were good and it was known that the behavior would be greatly improved by the addition of power for flareout and landing. Acceptable rates of descent below 35 knots, as indicated in figure 7, were reduced because of a lack of directional and longitudinal control. Approach speeds lower than 35 to 40 knots were not used for STOL landings because of inadequate directional and longitudinal control for the landing.

A modification was made to the leading edge of the VZ-2 wing which provided, effectively, about 6° of droop. This change so greatly improved the characteristics of the aircraft as indicated by the lower boundaries in figure 7 that serious stall limitations in descent and level-flight deceleration were essentially eliminated from the range of practical flight operation, at least at incidence angles up to 50°. With the modified wing, the aircraft has become, by comparison with the original configuration, a pleasure to fly.

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Examination of limiting operating conditions in deceleration and descent for the VZ-4 aircraft at the Langley Research Center has not been completed. However, stalling of the outboard sections of the wing in level flight and descent at duct angles over about 30° has produced buffeting and alternate left and right wing dropping of generally small magnitude at moderate airplane angles of attack. Although it is possible to avoid the stalling by keeping the airplane angle of attack low enough, it may not be operationally practical to do so in steep descents. Also, if a vertical landing is to be made, the stall angle must be exceeded at some stage in the landing maneuver. Severe wing dropping has been experienced in this aircraft when the stall angle of attack has been slowly approached. The roll control was not adequate to keep the aircraft upright under these conditions.

Glide-Path Control

It has been generally assumed that operation of V/STOL types at low speed as required in a steep approach means operating on a steeply rising "backside" of the power-required curve. Operation in this region is generally found more difficult than operation above the speed for minimum power required because any speed change, whether due to attitude correction by the pilot, gusts, or power change, will result in deviation from the desired flight path if power adjustments are not made. Consequently, corrections to glide path are made primarily by power changes, a more complex technique than one where attitude corrections can be used. The need for this type of operation is particularly undesirable during instrument flight.

The power-required curves usually presented for the VTOL aircraft, which show a steeply rising variation below the speed for minimum power, are obtained with some parameter, such as fuselage attitude, constant and with the tilting elements varied to establish the trim speeds for the powers shown. However, this does not represent the characteristics the pilot appreciates during an approach. On the approach, particularly on instruments, the pilot would very probably use a fixed-tilt configuration.

Figure 8 shows results of tests with the VZ-2 aircraft at fixed wing
L incidence when speed is varied by attitude change. In this case there
1 is no variation in power required so that difficulties of "backside"
4 operation would, at least, be minimized. However, the flat curve is a
1 function of the change in drag of the fuselage with angle of attack and
9 is not apt to be so favorable on cleaner, future designs.

The power-required characteristics of the VZ-4 aircraft are shown in figure 9. The slope of the curve at constant duct angle is actually favorable for a range of speeds. Thus, the glide-path control on the approach is much less a problem than was supposed at an earlier stage. This characteristic is fundamental to the fixed-wing configuration as long as the wing remains unstalled.

Height Control

Good height control in hovering and landing is very important and is a function of how immediately and accurately the pilot can control the thrust. In the case of the XV-3 and VZ-2 aircraft, as for helicopters, the pilot has direct control of the rotor pitch and height control is not a problem.

For the other aircraft a change in propeller rotational speed or propeller governing must occur following throttle operation to obtain the desired thrust change. The time delay in these systems is large enough to force the pilot to operate the throttle very gingerly to offset his inability to anticipate the final result. There is a strong tendency for the unindoctrinated pilot to establish immediately an oscillation in height with the maximum thrust change dangerously out of phase with the pilot's desires. On the other hand, the experienced pilot finds it necessary to plan continually in advance to avoid situations in which large or rapid thrust changes may be required near the ground.

The requirement for a short-time constant in thrust response is unimportant well away from the ground and in forward flight. On the other hand, rotor-pitch governing is necessary in forward flight to prevent rotor and engine overspeeding or to prevent large power variations if governed by fuel-flow changes.

GENERAL CONSIDERATIONS

The operation of the tilting elements of all the aircraft has proved little more complex than the operation of flaps or speed brakes on an airplane. It has been quite natural to use the tilting components as a speed control at the low end of the speed range. All of the aircraft under discussion have a switch on the control stick for operation of the tilting elements. Thus, tilt is accomplished without necessity for removing the hands from any of the primary controls.

In the case of the XV-3 aircraft, a large speed range can be covered without tilting the rotor masts forward and without the necessity of large fuselage tilts because longitudinal rotor feathering is provided. This flexibility of control leaves an added decision up to the pilot as to how and when to use the rotor tilt.

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The undesirable complexity of operation of these vehicles is encountered when additional factors such as trim surface settings, engine power, angle of attack, speed, or other things must be programed in sequence with the tilting elements to convert successfully. Only one of these aircraft, the VZ-4, at present requires such programing, and then during the slowdown to hovering. The fact that all the aircraft do not require special techniques in conversion is, indeed, remarkable.

With regard to cockpit instrumentation, it is felt that presentation of angle-of-attack information to the pilot is not necessary for the tilt-wing aircraft. Since operation will probably involve partial stalling during some phase of flight, the stalling must always be "flyable." With fixed-wing types of V/STOL, however, it may be desirable or necessary to avoid stalling or to know when it is imminent. In these cases angle-of-attack instrumentation is necessary.

CONCLUSIONS

Handling qualities experience with the Bell XV-3, Vertol VZ-2, Curtiss-Wright X-100, and Doak VZ-4 aircraft have indicated that:

1. Hovering control is inadequate in some cases. However, guidance with respect to requirements for adequate control is available.

2. Ground interference on the VTOL aircraft can cause serious control problems and results in greater demands for control power than for helicopters.

3. The aircraft fly through conversion in both directions with remarkably few problems. Vibration arising from the rotor systems has been low for all of them. The VZ-4 and X-100 aircraft have been notably smooth in this respect.

4. Stalling of wing surfaces has provided some limitation, particularly for the VZ-2 aircraft, and to a lesser extent for the VZ-4 aircraft. However, the VZ-2 is a rudimentary form of tilt-wing aircraft, and known stall-alleviation principles will be applied in design of later configurations. Relatively simple methods of stall protection can be applied to the VZ-4 aircraft. The X-100 aircraft suffers no apparent stall problems.

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5. Positive and accurate height control is very important in vertical take-offs and landings. Present experience indicates that a satisfactory system requires direct control of rotor pitch by the pilot in vertical flight, whereas governing systems will be necessary for forward flight.

6. During a critical maneuver such as conversion from an approach configuration to a vertical landing, the pilot should have to operate only the following controls: the stick, the pedals, the power lever, and a control for the tilting elements. It should not be necessary for the pilot to remove his hand from the stick or power lever during such a maneuver.

7. Angle-of-attack indication for the pilot is not necessary for the tilt-wing type but will be necessary for the fixed-wing types.

REFERENCE

1. Schade, Robert O.: Ground Interference Effects. (Prospective NASA Paper.)

TABLE I

STABILITY AND CONTROL SUMMARY FOR VTOL RESEARCH AIRCRAFT

PHASE OF FLIGHT

STABILITY OR CONTROL AXIS	HOVERING	ACCELERATING CONVERSION	CRUISE	DECELERATING CONVERSION	DESCENT	LANDING
LATERAL						
STABILITY		V				
CONTROL	D				D	D
LONGITUDINAL						
STABILITY	V		BV			
CONTROL	V					
ADVERSE TRIM REQUIREMENTS		CD		CD		
DIRECTIONAL						
STABILITY	BCDV	V		V	V	
CONTROL	BCDV	V		V	V	V

B, XV-3
C, X-100
D, VZ-4
V, VZ-2

AIRCRAFT SYMBOLS IN TABLE INDICATE SIGNIFICANT AREAS.

TABLE II

FACTORS THAT INFLUENCE HANDLING QUALITIES OF VTOL RESEARCH AIRCRAFT

PHASE OF FLIGHT

FACTOR	HOVERING	ACCELERATING CONVERSION	CRUISE	DECELERATING CONVERSION	DESCENT	LANDING
GROUND-DOWNWASH INTERFERENCE DISTURBANCES	BCDV	BCV				BCDV
GROUND EFFECT ON POWER REQUIRED	C	C				
ADVERSE STALL EFFECTS				DV	DV	
GLIDE-PATH CONTROL					DV	
HOVERING HEIGHT CONTROL	CD					CD

B, XV-3
C, X-100
D, VZ-4
V, VZ-2

AIRCRAFT SYMBOLS IN TABLE INDICATE SIGNIFICANT AREAS.

BELL XV-3 AIRCRAFT

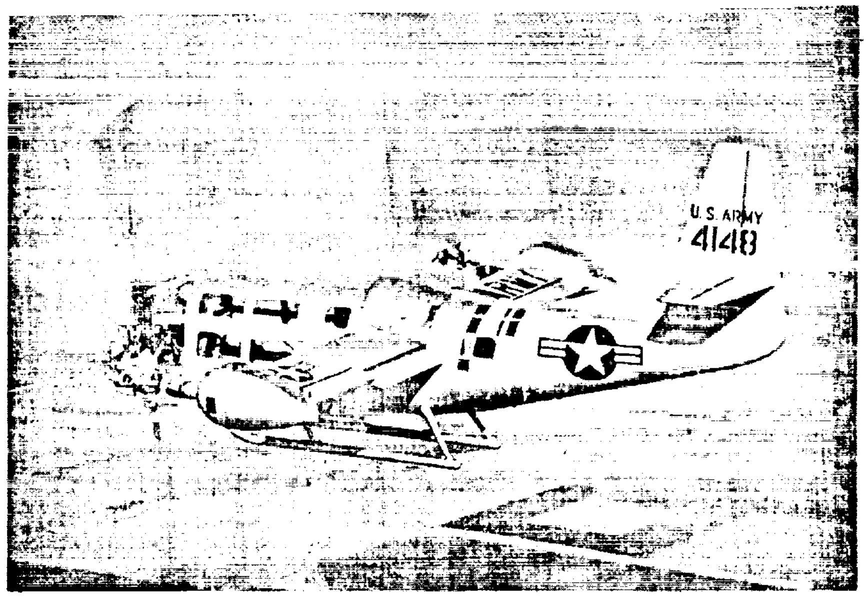

Figure 1

VERTOL VZ-2 AIRCRAFT

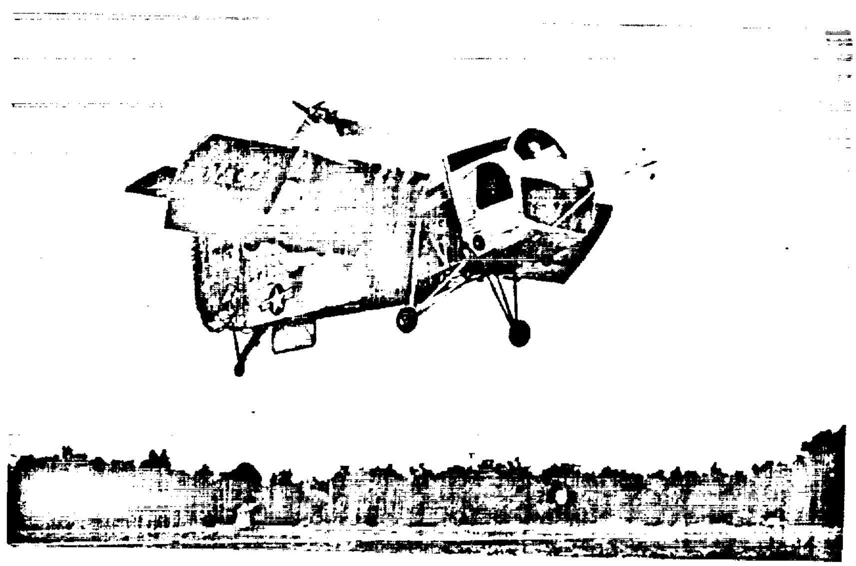

Figure 2

CURTISS-WRIGHT X-100 AIRCRAFT

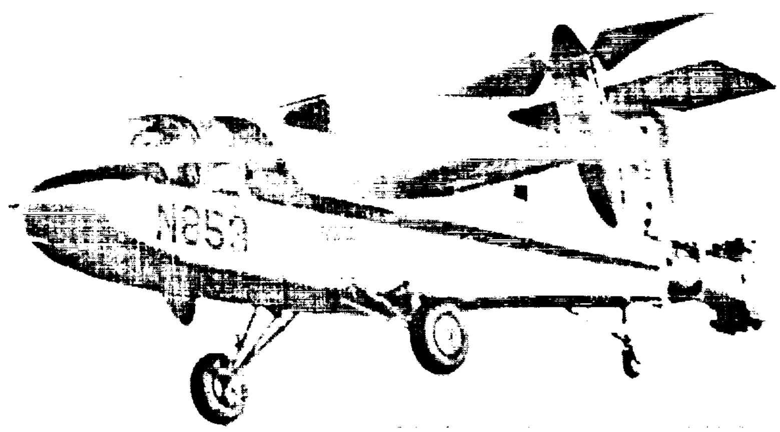

Figure 3

DOAK VZ-4 AIRCRAFT

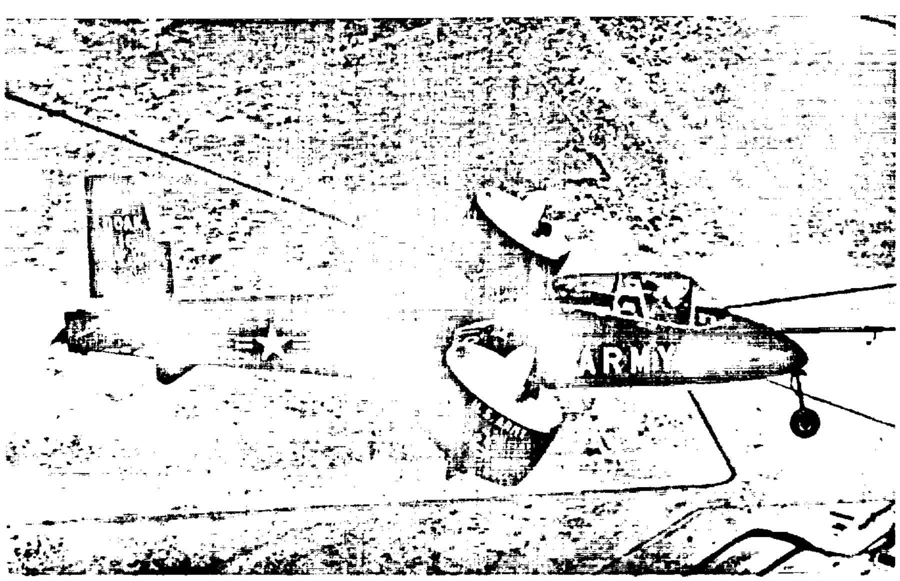

Figure 4

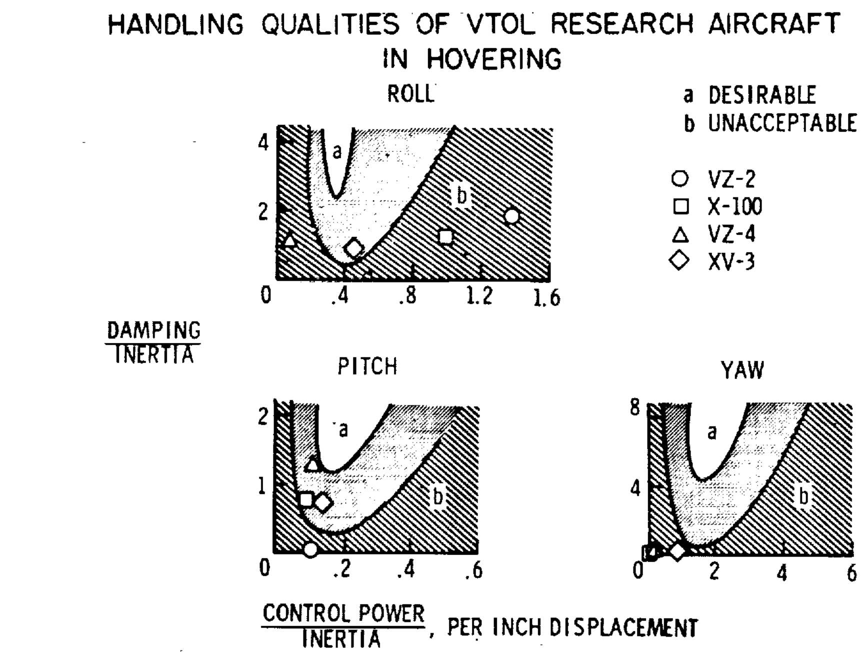

Figure 5

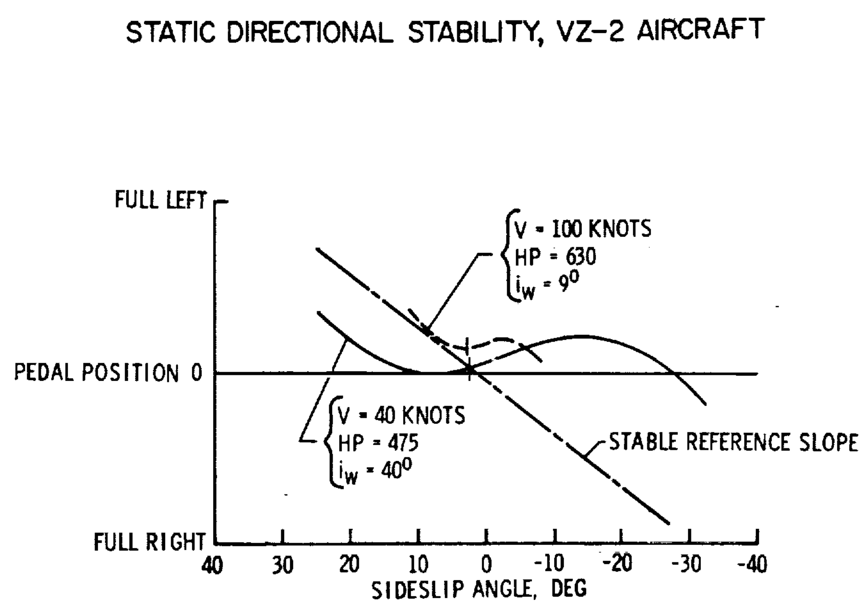

Figure 6

RATE-OF-DESCENT LIMITATIONS DUE TO STALLING, VZ-2 AIRCRAFT

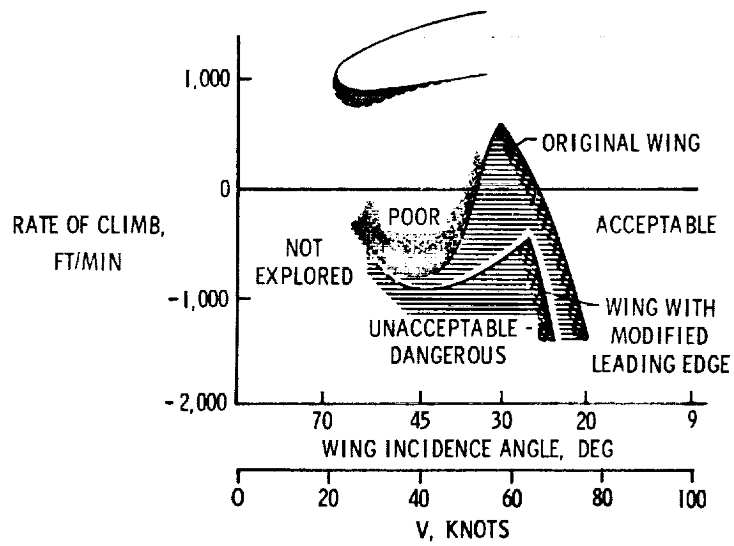

Figure 7

POWER REQUIRED FOR LEVEL FLIGHT, VZ-2 AIRCRAFT

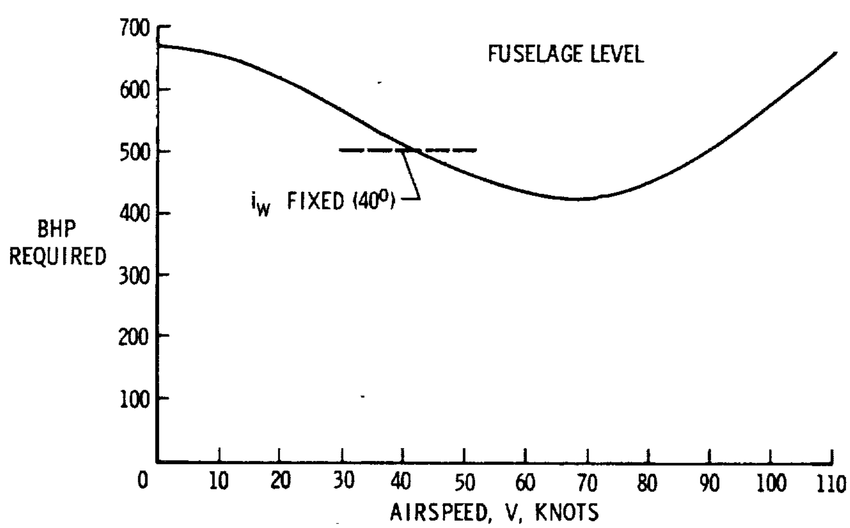

Figure 8

POWER REQUIRED FOR LEVEL FLIGHT, VZ-4 AIRCRAFT

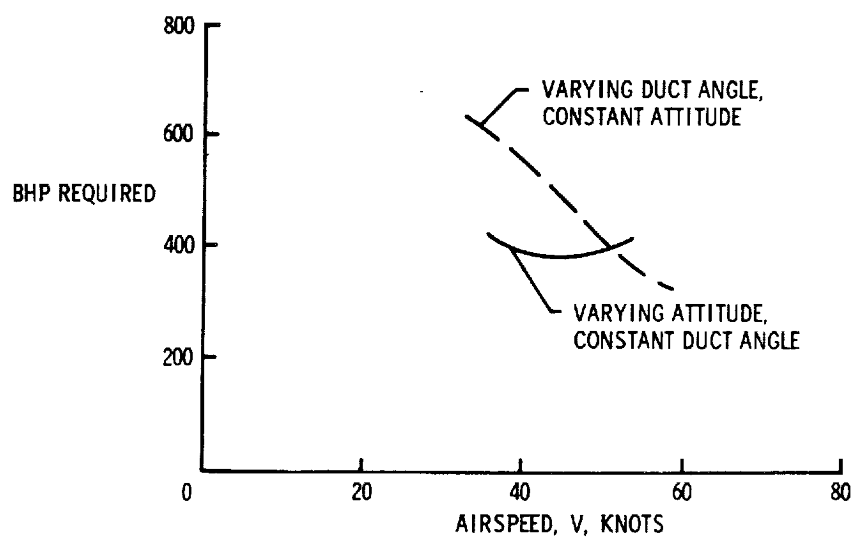

Figure 9