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Summary

As part of the NASA General Aviation Stall/Spin Program, a simulation study was conducted to investigate the piloting problems associated with failure of an engine on a generic light twin-engine airplane. A primary piloting problem for a light twin-engine airplane after an engine failure is maintaining precise control of the airplane in the presence of large steady control forces. To address this problem, a simulated automatic trim system which drives the trim tabs as an open-loop function of propeller slipstream measurements was developed. The simulated automatic trim system was found to greatly increase the controllability in asymmetric powered flight without having to resort to complex control laws or an irreversible control system. However, the trim-tab control rates needed to produce the dramatic increase in controllability may require special design consideration for automatic trim system failures. Limited measurements obtained in full-scale flight tests confirmed the fundamental validity of the proposed control law.

Introduction

One of the most serious failures which can occur on any airplane is the failure of an engine. For light single-engine airplanes such a failure is especially serious because the airplane must immediately descend regardless of the existence of a suitable landing area within gliding distance. The failure of one engine on a twin-engine airplane is, in theory, far less serious because it is usually assumed that the operative engine will make it easy to reach a suitable airport and make a safe landing. Unfortunately, this assumption is not always justified for light twin-engine airplanes (referred to as light twins in this paper). Recent accident statistics (ref. 1) show that the fatality rate from engine failures for light twins is twice that for light single-engine airplanes.

A series of wind-tunnel studies of light twins was conducted in the late 1960s and early 1970s. (See refs. 2 through 5.) Although these studies provided an extensive aerodynamic data base, no attempt was made to evaluate the unique piloting problems of the light twin or to explore the use of automatic control system concepts to lighten the pilot workload and enhance safety. The objectives of the subject simulation study were to develop an automatic trim system concept and to evaluate its effectiveness in reducing the pilot workload following failure of an engine. To support the simulation results, a brief full-scale flight test program was also conducted to obtain data to demonstrate the feasibility of the proposed control law for the automatic trim system.

Symbols

The axis system X, Y, Z used in this study is a body-fixed system as shown in figure 1.

C_h	generic hinge-moment coefficient, $\frac{\text{Hinge moment}}{\bar{q}_\infty S_i c_i}$
ΔC_h	change in generic hinge-moment coefficient due to automatic trim system
C_{h_δ}	$= \frac{\partial C_h}{\partial \delta}$
$C_{h_{\delta_{tab}}}$	$= \frac{\partial C_h}{\partial \delta_{tab}}$
c_i	chord of control surface (i = elevator, aileron, or rudder), ft
F_e, F_a, F_r	control forces for elevator, aileron, and rudder pilot controls, lbf
$\hat{F}$	residual engine-inoperative control force with automatic trim system on, percent of unaugmented force
ΔF_i	change in control force due to automatic trim system (i = elevator, aileron, or rudder), lbf
f, f'	function relationships (see eq. (1))
G	gearing ratio in control system, surface travel divided by pilot control travel, rad/ft
h	altitude, ft
$\dot{h}$	rate of climb, fpm
K_f	forward gain of automatic trim system, deg
$K_{f,o}$	nominal forward gain of automatic trim system, deg
K_r	gain of electric trim motor in automatic trim system, 1/sec
$\bar{q}_d$	differential slipstream dynamic pressure, $\bar{q}_r - \bar{q}_l$, lbf/ft^2
$\bar{q}'_d$	differential slipstream dynamic pressure after deadband (see fig. 11), lbf/ft^2
$\bar{q}_l$	dynamic pressure in left slipstream, lbf/ft^2

$\bar{q}_l\|_{sym}$	dynamic pressure in left slipstream measured in symmetric powered flight, lbf/ft^2
$\bar{q}_r$	dynamic pressure in right slipstream, lbf/ft^2
$\bar{q}_\infty$	dynamic pressure in free stream, lbf/ft^2
$\bar{q}'_\infty$	limited dynamic pressure in free stream, lbf/ft^2
S	wing area, ft^2
S_i	area of control surface (i = elevator, aileron, or rudder), ft^2
s	Laplace operator, rad/sec
T_l	thrust of left engine, lbf
T_r	thrust of right engine, lbf
T'_c	thrust coefficient, $\frac{\text{Total thrust}}{\bar{q}_\infty S}$
T'_d	differential thrust coefficient, $\frac{T_r - T_l}{\bar{q}_\infty S}$
Δt	response time of automatic trim system, sec
V	true airspeed, knots
V_{mc}	minimum engine-inoperative control speed (propeller windmilling), knots
V_p	minimum engine-inoperative trim speed (propeller feathered), knots
V_s	stall speed with one engine inoperative, knots
$V_{Y,se}$	airspeed for best rate of climb with engine inoperative, knots
W	weight of airplane, lbf
$(Y_\beta)_B$	side force of fuselage due to sideslip, lbf
$(Y_\beta)_{VT}$	side force of vertical tail due to sideslip, lbf
$Y_{\delta r}$	side force due to rudder deflection, lbf
α	angle of attack, deg
β	angle of sideslip, deg
δ	generic primary control surface position, deg
$\delta_e, \delta_a, \delta_r$	elevator, aileron, and rudder control positions, deg
$\delta_{e,\text{tab}}, \delta_{a,\text{tab}}, \delta_{r,\text{tab}}$	elevator, aileron, and rudder trim-tab positions, deg
δ_{tab}	generic trim-tab position, deg
$(\delta_{\text{tab}})_{\text{pilot}}$	component of trim-tab deflection commanded manually by pilot through cockpit trim wheel, deg
$(\delta_{\text{tab}})_{\text{sys}}$	component of trim-tab deflection commanded by automatic trim system, deg
ϕ_c	trimmed roll angle commanded by automatic trim system, deg
ψ, θ, ϕ	yaw, pitch, and roll Euler attitude angles, deg
$\dot{\psi}$	heading rate, deg/sec

Description of Simulation

The Langley General Aviation Simulator was used in this study. The individual elements of the simulation system are shown in figure 2 and are described in the following discussion.

Hardware

The simulation cockpit consisted of a portion of the fuselage of an actual light twin. The cockpit was mounted on a three-degree-of-freedom (DOF) motion system which provided pitch, roll, and heave motion. (See fig. 3.) The motion base is described in detail in reference 6. The instrument panel contained instruments typical of those on current light twins and included displays of attitude, airspeed, altitude, rate of climb, heading, and a turn and slip indicator. (See fig. 4.) The simulator also had hydraulic control loaders for the elevator, aileron, and rudder cockpit controls. The force on each control was programmed on the computer as a function of the cockpit trim wheel positions and the airplane flight condition. There were also cockpit controls for the flaps, landing gear, and cowl flaps. A system of nine speakers around the interior of the cockpit provided simulated wind noise proportional to airspeed and an engine noise proportional to engine thrust. Attached below the knob on each propeller pitch control lever was a small cueing light which was activated whenever there was a significant difference in thrust on the two engines. The light on the propeller lever located on the side with the smaller thrust was activated to indicate the propeller which should be feathered.

A closed-circuit color television system provided a 48° by 26° visual scene of a terrain board which was displayed through a virtual image system forward of the front window. In addition, a series of computer-drawn clouds was superimposed above the terrain scene for better visual attitude reference during the climb after takeoff.

Aerodynamic Math Model

The overall objective in developing the simulation math model was to provide a generic model which was representative of current light twin-engine airplanes without attempting to simulate any specific configuration. As a result, information was drawn from several different sources to assemble the final model used in the study.

The major physical characteristics of the simulated airplane were as follows:

Weight, lbf	6200
Wing area, ft^2	196
Wing span, ft	40
Wing chord, ft	5.2
Engine power (total), hp	660
Roll inertia, slug-ft^2	11 000
Pitch inertia, slug-ft^2	5000
Yaw inertia, slug-ft^2	15 000

The aerodynamic math model was described in reference 7 and was originally developed from and followed the basic format of the simulation described in reference 8. As such it was made only as complex as was necessary to provide the fundamental characteristics of a light twin. In this formulation, most of the aerodynamic characteristics were nonlinear functions of angle of attack and thrust coefficient. However, at a given angle of attack and thrust coefficient, the variation of the aerodynamic forces and moments was assumed to be linear with control deflection and sideslip angle. For the sideslip characteristics, this formulation involved an extrapolation. That is, the simulated sideslip characteristics were assumed to be linear for all values of sideslip, whereas the data were measured in the tunnel for only ±8° of sideslip. Thus, nonlinear sideslip phenomena such as vertical tail stall were not modeled. Vertical tail stall can be an important limiting factor for asymmetric thrust conditions as described in reference 9. The simulated engines were turbocharged so that the developed horsepower was independent of altitude.

The two main modifications to the simulation math model described in reference 8 were extension of the angle-of-attack range from 16° to 24° and addition of asymmetric power effects. These modifications were based primarily on the full-scale wind-tunnel tests reported in reference 2. The asymmetric power wind-tunnel data were measured at thrust coefficients corresponding to climb power or less ($T_c' = 0.28$ and $T_d' = 0.14$). At stall airspeeds with full power, however, the thrust coefficients can be substantially higher than 0.28. The data, therefore, had to be linearly extrapolated to the higher thrust coefficients needed for the simulation. A second area of extrapolation was necessary when extending the angle-of-attack range. The control derivatives had to be estimated for angles of attack from 16° to 24°. The remainder of the aerodynamic characteristics at angles of attack from 16° to 24° were presented in reference 2.

Engine failures were modeled as a simple first-order decay of thrust with a 0.67-sec time constant. The single-engine rolling and yawing moments at a given angle of attack were made two-segment linear functions of the differential thrust coefficient T_d'. The effects of feathering a propeller were simulated by a change in yawing moment and drag based on the wind-tunnel data for another twin-engine configuration reported in reference 10.

The control forces were calculated by using the hinge moments measured in the wind-tunnel tests of reference 2. The measurements were made for different angles of attack, sideslip, and control deflections with zero trim-tab deflection. The trim-tab hinge-moment coefficients, therefore, had to be estimated by assuming a given level of trim authority with an engine inoperative as discussed later. The effects of the trim tabs on the total aerodynamic forces and moments on the airplane were arbitrarily set equal to zero.

The simulation math model was implemented on an all-digital computer system which operated in real time at a rate of 32 frames/sec.

Simulator Validation

The simulation was validated by using the qualitative evaluations of four research pilots although only three of these pilots participated in the research program. These pilots evaluated the performance characteristics, the static and dynamic control responses, and the trim changes due to configuration changes. During the course of this validation procedure, the primary research pilot made qualitative flight tests of two different light twins to compare specific responses with those of the simulated airplane. Both symmetric and asymmetric power conditions were evaluated. Several modifications to both the static and dynamic aerodynamic characteristics of the preliminary simulation model were made based on the evaluations of the primary pilot. The major modifications were to the engine math model and the control forces. Other modifications were made to the dihedral effect and the yaw damping. The net effect of these changes is reflected in the static and dynamic characteristics, which are presented later.

Automatic Trim System

The automatic trim system was developed by using the simulator. The concept which evolved is described in the following sections. The system is automatic in the sense that it changes the trim-tab positions without pilot input. However, it does not provide an exactly trimmed airplane because it has no feedback of the airplane state. To provide an exact, hands-free trim, the pilot must make small manual trim adjustments.

Hardware

A pictorial representation of the simulated automatic trim system is shown in figure 5. The main components of the automatic trim system were the slipstream dynamic-pressure sensors, a computer, a trim-tab motor, and a mechanical summer. Alternate configurations might have separate trim tabs for the automatic trim system or hydraulic actuators on the primary control surfaces. The results of the present study would be equally applicable to any of these automatic trim systems. In an operational automatic trim system there would also be cockpit controls and safety devices to detect and correct for a malfunction. For ease of illustration, figure 5 shows a trim motor for only the rudder, but the concept requires similar motors for the aileron and elevator.

Control Law

The generalized control law for the automatic trim system is given by

$$(\delta_{\text{tab}})_{\text{sys}} = f(T_d') = f'\left(\frac{\bar{q}_r - \bar{q}_l}{\bar{q}_\infty}\right) \tag{1}$$

A different application of this control law was used to drive each of the rudder, aileron, and elevator trim tabs. The function $f'(\ )$ is dependent on the combined thrust characteristics, the airplane stability and control characteristics, and the hinge-moment characteristics. In practice, the relationship would probably be determined most easily by establishing actual dynamic pressures and trim-tab deflections in stabilized, zero-control-force, engine-inoperative flight.

The control law is open loop in that there is no measurement of the trim-tab position, control force, or airplane state which is used to modify the commanded trim-tab position. The pilot must provide all stabilization of the airplane. However, as the airplane changes airspeed or the thrust developed by one engine changes, the commanded trim-tab position will change to account for the new conditions. For example, if an engine failed at a cruise flight condition, $\bar{q}_\infty$ would be relatively large and $(\delta_{\text{tab}})_{\text{sys}}$ would be relatively small. The asymmetries at a cruise flight condition are also relatively small so that the small $(\delta_{\text{tab}})_{\text{sys}}$ commanded by the automatic trim system would be sufficient. As the airplane slowed down to land, $\bar{q}_\infty$ would become smaller and $(\delta_{\text{tab}})_{\text{sys}}$ would become larger to counteract the increasing asymmetries at the lower airspeeds.

Inasmuch as the trim-tab hinge-moment coefficient was a constant in this simulation, the change in the trim-tab position was equivalent to a change in the hinge-moment coefficient of the primary control surface

$$\Delta C_h = C_{h_{\delta_{\text{tab}}}} (\delta_{\text{tab}})_{\text{sys}} = C_{h_{\delta_{\text{tab}}}} f'\left(\frac{\bar{q}_r - \bar{q}_l}{\bar{q}_\infty}\right) \tag{2}$$

or a change in the control force

$$\Delta F_i = -G\bar{q}_\infty S_i c_i \, \Delta C_h = -G\bar{q}_\infty S_i c_i C_{h_{\delta_{\text{tab}}}} f'\left(\frac{\bar{q}_r - \bar{q}_l}{\bar{q}_\infty}\right) \tag{3}$$

where i = elevator, aileron, or rudder.

Any device (for example, a hydraulic actuator) which produces a change in the control force as given by equation (3) would produce results identical to those for the present automatic trim-tab system. Thus, as stated earlier the results presented herein could apply to a variety of hardware implementations of this concept and are not limited to an automatic trim system which drives the trim tabs.

Flight Test Validation of Control Law

The primary objective of the flight tests was to obtain data to demonstrate the feasibility of the proposed control law for the automatic trim system. The second objective was to assess the measurement errors by using a single slipstream sensor at a fixed location in the slipstream. Such measurement errors would manifest themselves to a pilot using the automatic trim system as residual control forces as discussed in depth in the section "Residual force variations." If the residual forces due to these errors get too large, the improvement in the handling qualities due to the automatic trim system will be lessened.

Differential thrust coefficient is really a function of the average total pressure over the entire cross section of the slipstream (ref. 11) and not the dynamic pressure at a single point. In the present automatic trim system, the difference between total pressure and dynamic pressure is assumed to be absorbed in the functional relationship given in equation (1) inasmuch as the dynamic-pressure sensor is assumed to be at a fixed location in the slipstream. In a practical automatic trim system, a total-pressure sensor (or multiple total-pressure sensors) may have to be used as discussed in reference 12.

The light twin used to conduct the exploratory flight test experiments is shown in figure 6. The airplane had a maximum takeoff weight of about 4800 lbf, two 240-hp normally aspirated engines, and two constant-speed, full-feathering propellers rotating in the clockwise direction as viewed from the rear of the airplane.

A miniature anemometer, described in reference 13, was mounted on the inboard side of the left engine cowling as shown in figure 7. No attempt was made to determine the optimum location of the anemometer from a slipstream measurement standpoint. Instead the location was picked primarily for ease of installation. The centerline of the anemometer was aligned with the thrust axis 6 in. from the side of the cowling at a 0.60-propeller-radii location with respect to the thrust axis. The longitudinal position of the anemometer was approximately 0.70 propeller radii behind the propeller disk. The anemometer produced a variable frequency electrical output which was calibrated in terms of true airspeed and measured by a time-averaging frequency counter over a 10-sec period.

The control surface deflections were inferred from the position of the cockpit controls. That is, the trim-tab position was assumed to be a linear function of the rudder trim-wheel position, and the rudder position was likewise inferred from the position of the rudder pedals. The airplane airspeed system was used to determine the free-stream dynamic pressure.

The tests were conducted at a slow airspeed (90 knots) in order to accentuate the engine-inoperative asymmetries. The smaller asymmetries at higher airspeeds (over 120 knots) were often masked by the scatter in the data. The flight test measurements had to be made in two steps because there was an anemometer on only the left engine. The first step involved symmetric power measurements of the (left) propeller slipstream velocities for various power levels (combinations of manifold pressure and propeller speed). The second step was to set up the same flight and power condition on the right engine but with the left engine either windmilling (minimum throttle and maximum prop control positions) or turned off and propeller feathered. Under these conditions, the airplane was banked 5° into the operative (right) engine and the rudder trim wheel was then turned (rudder pedals floating free) until the heading rate was forced to zero. Trim-wheel position, rudder pedal position, and (left) slipstream velocity were then recorded in the stabilized flight condition.

The basic assumption used in the reduction of the flight test data was that the dynamic pressure in the right slipstream $\bar{q}_r$ during the asymmetric power runs was the same as that measured in the left slipstream $\bar{q}_l|_{\text{sym}}$ in the earlier symmetric power runs at the same condition. In other words,

$$\bar{q}_r = \bar{q}_l|_{\text{sym}} \tag{4}$$

With this relationship, it was, therefore, possible to construct a series of data points of trim-tab position versus differential slipstream dynamic pressure for the asymmetric power runs.

The test procedure for assessing the propeller slipstream measurement errors was to adjust the manifold pressure as the propeller speed was varied so that the rate of climb was always zero at a constant airspeed. This procedure assured that the net thrust was always constant regardless of the propeller speed (blade angle) and the radial disk loading. If the slipstream measurements were a perfect indication of thrust, the slipstream velocity would not change. Any actual change is a measurement error as far as the automatic trim system is concerned.

The results of the engine-inoperative flight tests designed to verify the validity of the control law used in the simulation tests are presented in subsequent paragraphs. The change in trimmed rudder position as a function of the differential thrust parameter $(\bar{q}_r - \bar{q}_l)/\bar{q}_\infty$ is shown in figure 8. The rudder position was reversed (i.e., to the left although a failed left engine usually requires a right rudder position) for all the tested conditions except when the differential thrust parameter was greater than 0.6. This reversed control was a result of two factors: (1) the right (operative) engine could not develop full power at the test altitude and (2) the airplane was banked 5°, which produced a sideslip which helped counter the yaw asymmetry. For three of the data points, the differential thrust coefficient was actually negative; this indicated more thrust for the left (failed) engine than for the right (operative) engine. Two of the points are expected because they are for an essentially windmilling right (operative) engine which was removing more energy from the airstream than the left (failed) engine which had a feathered propeller. The third point must be due to scatter in the data possibly due to lack of repeatibility in setting power levels. However, there appears to be a nearly linear relationship between the change in trimmed rudder position and the differential thrust parameter regardless of whether the propeller on the failed engine was windmilling or feathered. Thus, the data indicate that the proposed control law (eq. (1)) is viable because the change in the trimmed rudder position is related to a change in hinge-moment coefficient as discussed earlier.

The corresponding trim-tab data are presented in figure 9. The trim-tab deflections are again reversed because of the low power on the operative engine and the 5° bank, but this time the mechanical stop (in the reversed direction) was reached at a differential thrust parameter of about zero. Beyond this point the pilot had to apply a slightly reversed pedal force to stop the heading rate. The correlation between the rudder trim tab and the differential thrust parameter was not as good as that for the rudder itself probably because of friction in the control system. However, the data still suggest that the proposed control law is viable.

The variation of the measured propeller slipstream velocity with propeller speed at constant thrust is shown in figure 10. The slipstream velocity increased as the propeller speed increased; this indicates that the propeller loading was shifting from the propeller tips inward. The variation was only ±5 percent, which would translate into a variation of about ±10 percent in the dynamic pressure. This variation is well within the ±25-percent band about nominal in which the handling qualities were found to be substantially improved, as will be discussed later in the section "Piloted Simulation Maneuvers."

Simulation Representation of Automatic Trim System

The block diagram for the simulated automatic trim system is shown in figure 11. The first step in the simulation was to calculate the theoretical propeller slipstream dynamic pressures. Propeller momentum theory was used to relate the propeller thrust and the free-stream dynamic pressure to the slipstream dynamic pressure. The calculated propeller slipstream dynamic pressures were used to activate the cueing lights on the cockpit propeller pitch controls and also to calculate the differential thrust coefficient T_d'. The differential thrust coefficient could have been calculated more directly from the right and left propeller thrusts without the intermediate step involving the slipstream dynamic pressures. However, in order to get the signals for the propeller cueing lights, the present approach was taken. The slipstream dynamic pressure as calculated in figure 11 from propeller momentum theory is valid only far downstream from the propeller. It is assumed in the simulation that the dynamic pressure measured by a real sensor located near the propeller disk would still be related to the thrust even if it was not exactly the relationship shown in figure 11.

The differential thrust coefficient T_d' was multiplied by a simple gain K_f to produce the desired change in trim-tab position. The actuator was assumed to be an electric motor which ran at a constant speed, K_r, and produced a final position output proportional to the input. The output of the motor was assumed to be mechanically summed with the pilot's trim-tab input to produce the total trim-tab position.

The effect of the trim-tab position was modeled in the simulation as adding an increment to the total hinge-moment coefficient as shown earlier in equation (2). If the pilot-applied control force is zero or constant, the change in the trim-tab position results in a change in position of the primary control surface. The position of the primary control surface is then proportional to the ratio of the tab and primary surface hinge-moment coefficients, $C_{h_{\delta_{\text{tab}}}}/C_{h_\delta}$. As long as the trim tab does not reach its mechanical travel limits, the net effect of the automatic trim system after the trim tab has reached its final value is proportional to the product of the automatic trim system gain K_f and the ratio of the hinge-moment coefficients.

Automatic Trim System Specification

The performance of the automatic trim system is determined by four parameters. Variations of these parameters about a nominal set of values were used to study the effect of the automatic trim system on the control of the airplane and the handling qualities. The four parameters are (1) the residual force $\widehat{F}$, (2) the response time Δt, (3) the minimum engine-inoperative trim speed V_p, and (4) the commanded trim roll attitude ϕ_c. These parameters are described in the following discussion.

The residual force $\widehat{F}$ was a parameter used to simultaneously vary all three automatic trim system gains by equal percentage amounts:

$$K_f = K_{f,o}\left(\frac{100 - \widehat{F})}{100}\right) \tag{5}$$

The nominal simulated automatic trim system gains $K_{f,o}$ for the aileron and the rudder were calculated from the zero-control-force trim-tab positions and differential thrust coefficients at a single airspeed. Thus, the simulated automatic trim system did not have gain scheduling as might be used on an optimized system on a real airplane.

The nominal automatic trim system gain for the elevator automatic trim system was calculated so that the longitudinal wheel force at $V_{Y,se}$ was reduced from about 20 lbf to about 10 lbf. That is, the unaugmented airplane had a large pitch-down trim change when the engine failed. This change was generally beneficial because it helped alleviate the natural tendency of the airspeed to get dangerously low. If the gain $K_{f,o}$ in the elevator system was set high enough to eliminate the pitch-down entirely, the tendency toward low airspeeds was accentuated which was objectionable to the pilots. Thus, the nominal gain was selected to eliminate about half the pitch-down trim change of the unaugmented airplane.

When the residual force parameter was zero, all the gains were equal to their nominal values as described previously. The name "residual force" comes from the fact that the gains govern the amount of residual force the pilot has to apply to stabilize the airplane. When the residual force parameter was 100 percent, $K_f = 0$, the automatic trim system produced no change in the trim-tab positions and the automatic trim system was essentially not active. When the residual force parameter equaled its nominal value of 0 percent $K_f = K_{f,o}$, the automatic trim system produced the most nearly trimmed airplane. The pilot might or might not elect to manually retrim the airplane to a completely stabilized, zero-control-force condition. The motivation for varying the residual force parameter was to determine how sensitive the handling qualities were to the previously discussed uncertainties that might be present in the operational measurement of the differential thrust coefficient by using a single slipstream sensor.

The response time Δt is simply the time it takes the trim tabs to reach their steady state after an engine failure. Since the simulated electric trim motor ran at a constant speed, the response time was given by

$$\Delta t = \frac{(\delta_{\text{tab}})_{\text{sys}}}{K_r}$$

where $(\delta_{\text{tab}})_{\text{sys}}$ was defined for a full asymmetric power condition (propeller feathered) at an airspeed of 109 knots. The response time was varied by changing K_r.

The last two parameters, V_p and ϕ_c, modified the force characteristics in only the roll and yaw axes and did not affect the pitch axis force characteristics. The minimum engine-inoperative trim speed V_p is defined as the minimum speed at which full trim-tab deflection is capable of trimming the control forces to zero with full asymmetric power (propeller feathered) and the airplane banked 5° into the operative engine. In reality this parameter is used to define the authority of the trim tabs (or for a powered control system, the torque-producing capability of the powered actuators). In this simulation study, this parameter was varied by adjusting the aileron and rudder trim-tab hinge-moment coefficients while holding the trim-tab travel fixed and was the criterion used to estimate the values of the trim-tab hinge-moment coefficients. As the simulated trim tabs became more powerful, V_p decreased. If $V_p < V_s$ as in the nominal automatic trim system, then the control forces can be trimmed for all usable airspeeds (for a powered control system the actuators would have sufficient torque to provide adequate control surface deflection for all usable airspeeds). For an automatic trim system using trim tabs, the minimum engine-inoperative trim speed is really a characteristic of the simulated airplane and is not a characteristic of the automatic trim system. However, V_p still has a strong influence on the pilot's impression of how well the automatic trim system is working when the airspeed is below V_p.

Whenever the estimated trim-tab hinge-moment coefficients were decreased, the simulated automatic trim system gains $K_{f,o}$ were simultaneously increased so that the system would statically trim full asymmetric power conditions at the lowest practical airspeed. That is, the product of $K_{f,o} C_{h_{\delta_{\text{tab}}}}$ was maintained as constant as possible.

The commanded roll attitude ϕ_c is the absolute value of the trimmed roll attitude with the controls free and full asymmetric power (propeller feathered). It was varied by simultaneously adjusting the ratio of the aileron and rudder system gains to produce the desired attitude.

The nominal automatic trim system had the following characteristics:

$$\hat{F} = 0$$

$$\Delta t = 2 \text{ sec}$$

$$V_p < V_s = 85 \text{ knots}$$

$$\phi_c = 3^\circ \ (\beta = 0^\circ)$$

In hindsight it became apparent that the nominal value for V_p used in the simulation was unrealistically low—that is, the simulated trim tabs were more powerful than those on current light twins. Because of the effectiveness of the trim tabs (especially the rudder trim tab), the control forces on the simulated airplane could be trimmed with full asymmetric power and with the wings level at the airspeed for best single-engine rate of climb, $V_{Y,se}$. This excess effectiveness allowed the nominal simulated automatic trim system to be designed to drive toward a zero sideslip condition and maximum single-engine climb performance. In practice, slightly degraded climb rate performance would probably have to be accepted because most current operational trim-tab systems are only powerful enough to allow the control forces to be trimmed at a roll attitude of 5° and a nonzero sideslip condition. Therefore, the effect of more realistic, reduced trim-tab effectiveness (larger V_p) on overall performance of the automatic trim system was studied.

It should be emphasized that of the four parameters discussed only V_p was precisely defined in the simulator. The values quoted in this paper for $\widehat{F}$, Δt, and ϕ_c are only approximate averages because of the variations of the aerodynamic characteristics with angle of attack and because of the different engine-inoperative characteristics, depending on which engine had failed.

Ground-Based Simulation Tests

The ground-based simulation tests can be divided into two parts. The first part, which did not involve a pilot, was intended to document the static and dynamic characteristics of the simulated airplane. The second part involved the pilots' flying the simulator and their evaluation of the handling qualities.

Simulated Airplane Characteristics

In order to better understand the unique problems of single-engine flight in a light twin, the static trim characteristics of the unaugmented airplane were documented for a variety of flight conditions. Next, the static control forces were documented with and without the automatic trim system operative.

Some dynamic, controls-free time histories of sudden changes in asymmetric power conditions were also obtained. These included results for a sudden engine failure starting from a full-power flight condition and for a rapid power reduction on the operative engine starting from a stabilized engine-inoperative condition. The automatic trim system parameters for this documentation were

$$\widehat{F} = 0$$

$$\Delta t = 2 \text{ sec}$$

$$V_p = 100 \text{ knots}$$

$$\phi_c = 5^\circ$$

thus, V_p and ϕ_c were not at their nominal values.

Piloted Simulation Maneuvers

Three NASA research pilots served as test subjects in these tests. One pilot was designated the primary pilot, whereas the other two were back-up pilots. All three had extensive experience in both aircraft and simulators, and each was given a series of training maneuvers before evaluations of the handling qualities began.

Two maneuvers were used in the evaluations: (1) a takeoff followed by a sudden engine failure at an altitude of 200 feet and (2) a straight-in approach and landing from an initial altitude of 1100 ft with one engine already failed and the propeller feathered. Both maneuvers were conducted under simulated visual flight rules (VFR) conditions and with zero steady winds and no random turbulence.

The task for the takeoff maneuver was to simply maintain control after the engine failure, feather the correct propeller, and establish a climb at the airspeed for best single-engine rate of climb. The research pilots, especially the primary research pilot, became very proficient at flying this task after a few runs. The element of surprise was absent, and the only decisions the pilots had to make were which direction to apply the control inputs and which propeller to feather. Therefore, an artificial time delay of 3 to 5 sec following an engine failure was imposed on the primary research pilot before he was allowed to take any corrective action except to hold the wings level. The purpose of this delay was to simulate the period of confusion and indecision a real engine failure would probably produce on an average, unsuspecting pilot. The other two pilots were free to make all their control inputs as soon as they deemed necessary. In either situation, the emphasis of the evaluation was on the change in the pilot rating for a given configuration compared with the basic unaugmented airplane rather than on the absolute pilot rating. Table I presents the Cooper-Harper pilot rating scale used for the handling qualities evaluations.

The task for the landing maneuver was intended to simulate a misjudged, engine-inoperative approach. That is, the initial velocity and flight-path angle of the maneuver were such that if no correction was made, the landing would be far past the nominal landing point. The pilot was instructed to make a throttle chop on the operative engine at an altitude of 800 ft and hold his initial airspeed of 105 knots until the altitude reached 200 ft, at which point he was free to do what he judged best. At this point, the airplane would nominally be descending rapidly toward a touchdown substantially short of the runway and the pilot would have to add power on the operative engine to reach the runway. Thus, two large and abrupt power changes were introduced to simulate a misjudged approach and the resulting effect on the control of the airplane with one engine inoperative.

When evaluating a given configuration, each pilot was allowed to make as many runs as he thought necessary to give an accurate pilot rating. Usually two or three runs were sufficient, but sometimes as many as five or six runs were used. Often back-to-back runs with the automatic trim system off or with the nominal automatic trim system on were used for comparison.

Of the two maneuvers, the takeoff maneuver was judged by the pilots to be the most critical. As a result, it was used in evaluating the sensitivity of the handling qualities to variations in the characteristics of the automatic trim system. The primary research variables were the four parameters $\hat{F}$, Δt, V_p, and ϕ_c described earlier. Each parameter was varied individually while the other three parameters were held fixed at their nominal values. A table of the actual values of the parameters used is shown as follows:

Parameter	Nominal value	Research value
$\hat{F}$, percent	0	$^a -50$, $^a -25$, 25, 50
Δt, sec	2	0.5, 8, 32
V_p, knots	<85	$^b 90$, $^b 100$, $^b 110$, $^b 120$
ϕ_c, deg	3	$^a -1$, 5, 10

[a]Reversed direction.
[b]$\phi_c = 5°$ rather than nominal 3°.

Results and Discussion

The results are presented in three sections. The first two sections present the static and dynamic characteristics of the simulated airplane, and the third section presents the piloted maneuvers and evaluations.

Before the actual results are presented, it is helpful to review the basic physics of engine-inoperative flight. Generally, the rolling moment, the side force, and the yawing moment must all be balanced in order to stabilize the airplane on a desired heading. The net result of this requirement is that the sideslip angle will not be zero and its effect on the rolling moment, side force, and yawing moment can be as large as the engine-inoperative asymmetries themselves. When the sideslip angle is considered, there can be at least three control strategies as illustrated in figure 12. Using the first strategy, shown in figure 12(a), the pilot maintains roll attitude and sideslip (assuming a cockpit display of sideslip) at zero. Although the yawing moment is zero, the rudder generates an unbalanced side force which will cause the ball in the turn and slip indicator to be displaced away from the inoperative engine, and the airplane will have a steady heading rate toward the inoperative engine. Thus, the first strategy is not successful in stabilizing the airplane on a given heading even though the yawing and rolling moments are zero. If the pilot applies additional rudder deflection to stop the heading rate while maintaining the roll attitude at zero, the condition depicted in figure 12(b) will apply. In order to balance the side force due to the rudder deflection, a sideslip toward the inoperative engine will develop. This sideslip will, through the natural directional stability of the airplane, add to the engine-inoperative yawing moment; thus, even more rudder deflection will be required to attain equilibrium. The third and generally accepted control strategy is illustrated in figure 12(c). In this strategy, the pilot rolls the airplane 5° into the operative engine and adjusts the rudder deflection to stop the heading rate. The sideslip will now probably be toward the operative engine and there will be two favorable effects. First, the directional stability of the airplane will now subtract from the engine-inoperative yawing asymmetry and reduce the rudder deflection requirement. Second, there will be a side force due to the component of airplane weight toward the operative engine. This component of weight will help cancel the side force due to the rudder deflection.

In actual practice, many pilots may use a fourth control strategy. These pilots apply enough rudder force to stop the initial transient yawing motion of the airplane after the engine failure. They then hold a fairly constant rudder pedal force and make relatively higher frequency inputs with the lateral controls apparently to maintain a constant heading. The final average condition is an intermediate condition between those shown in figures 12(b) and (c). That is, the average roll attitude is somewhere between 0° and 5° toward the operative engine. The nominal simulated automatic trim system approximated this control strategy in that the trimmed roll attitude was about 3°.

Static Characteristics

The simulated control deflections and sideslip angle for control strategies shown in figures 12(b) and (c) are shown in figure 13 for various airspeeds. As the airspeed decreased, the rudder and aileron deflections required to stabilize the airplane increased regardless of the strategy used. In general, more control deflection was required to stabilize the airplane with the left engine inoperative than with the right engine inoperative. This is usually true when both propellers rotate in a clockwise direction as viewed by the pilot. In fact, as the airspeed decreased with the right engine inoperative and $\phi = -5°$, the airplane would stall before the rudder reached its 32° travel limit and was no longer able to counter the engine-inoperative asymmetries. With the left engine inoperative and with its propeller windmilling with $\phi_c = 5°$, maximum rudder deflection was required at 91 knots, which defined the minimum control speed V_{mc} for this simulation. The minimum control speed V_{mc} should not be confused with the minimum trim speed V_p. The minimum control speed is a function of the control deflections with a windmilling propeller, whereas the minimum trim speed is a function of the trim-tab position with a feathered propeller.

A more detailed look at the effect of roll attitude on the control deflections at a constant airspeed is shown in figure 14. By rolling the airplane from wings level to 5° into the operative engine, the rudder deflection required to stabilize the airplane was reduced more than 50 percent. The aileron deflection was simultaneously increased, but there was still considerable aileron deflection available. As the aileron control force was increased to roll the airplane into the operative engine, the rudder control force decreased. (See fig. 15.) For the present simulation, a 1-lb increase in aileron force reduced the rudder pedal force 8 lb. Thus, the aileron could be viewed as a very powerful boost for the rudder. This boost was accomplished, of course, through the change in sideslip and the resulting yawing moment produced by the directional stability of the airframe. If the sideslip becomes too large, however, the vertical tail may stall; therefore, there are practical limits to the boost which the ailerons can provide. Inasmuch as vertical tail stall was not modeled, these limits could not be determined in this study. The importance of the boost can be great if the rudder trim tab has limited authority. That is, without the sideslip generated when the airplane is rolled into the operative engine, the rudder trim tab on many airplanes may not be capable of deflecting the rudder far enough to counter the yawing asymmetries. The pilot would have to apply the additional rudder control force needed to stabilize the airplane.

Another limitation to the use of excessive roll attitude to control the engine-inoperative asymmetries is the associated penalty in climb performance. The nominal single-engine climb performance (propeller feathered) for this simulation was marginal and with either the flaps or gear extended it was not possible to climb. (See fig. 16.) The maximum rate of climb at $V_{Y,se}$ occurred at a roll attitude of approximately $-2.0°$. (See fig. 17.) A roll attitude of $-5°$, which is accepted engine-inoperative practice, produces a penalty of 80 fpm, whereas larger roll attitudes produce ever increasing penalties in climb performance.

The effectiveness of the automatic trim system in reducing the static control forces with an engine inoperative after all transients have died out and the airplane is stabilized is shown in figures 18 and 19. With the automatic trim system off and the trim-tab positions held constant, the control forces increased as the airspeed decreased. With the automatic trim system on, the control forces were greatly reduced compared with the automatic trim system off. The trim-tab positions increased as the airspeed decreased which helped compensate for the increased asymmetries at the lower airspeeds. Inasmuch as the automatic trim system did not close the loop on the control forces, the control forces were, in general, not zero because of the nonlinear airplane characteristics and the fact that gain scheduling was not used in the simulation. However, the forces were greatly reduced by the automatic trim system for this particular gain, and the pilots could not readily detect these small out-of-trim conditions especially at $V_{Y,se}$ (109 knots). The change in the force from system off to system on was directly proportional to the automatic trim system gain K_f. Thus, an error in this gain or any uncertainty in an operational measurement of slipstream dynamic pressure would be reflected in an equal percentage change in the reduction in force. This dependent relationship is the reason one of the primary research variables was the residual force parameter $\widehat{F}$, inasmuch as it affected K_f. (See eq. (5).)

Unlike the roll and yaw axes, the nominal pitch axis system was not designed to reduce the large longitudinal wheel force to zero as explained earlier. It was found that requiring the pilot to exert an aft control force to counter a nose-heavy condition helped to minimize the tendency for the airspeed to get dangerously low immediately after the engine failed on takeoff. The resulting force characteristics are shown in figure 20. At the airspeeds used in the takeoff maneuver (approximately 100 knots), the force is about halved. Although not readily apparent from the figure, the automatic trim system also reduces the slope of the curve and, thus, reduces the apparent stick-free static stability slightly. The main effect, however, is an offset in the force.

The pilot could fly the airplane with his feet on the floor with the automatic trim system on. That is, with the rudder pedals floating free ($F_r = 0.0$), the pilot could control the heading with the ailerons alone because the automatic trim system caused the rudder to float in the direction to counter the single-engine yaw asymmetry. At 110 knots, such a control strategy would result in a trimmed roll attitude of close to 5° and a total aileron control force of less than 3 lbf. (See fig. 21.) An aileron control force of less than 3 lbf is probably within the friction level of many general aviation control systems. (Control system friction was not considered in these calculations or in the piloted simulation.)

The effectiveness of this control strategy of letting the rudder pedals float free for different levels of asymmetric power is demonstrated in figure 22. That is, with the automatic trim system on, as the power level is increased on the operative engine, the automatic trim system added more and more trim-tab deflection so that the pilot had to apply very little additional lateral wheel force even though the control surface position and roll attitude were increasing with the power level. With the automatic trim system off, the pilot had to apply much more force and use larger roll attitudes. At full asymmetric power (100 percent on the right engine), the roll attitude was large with the automatic trim system off because the float angle of the rudder did not help counter the asymmetries. In fact, the sideslip for this condition may have been enough to stall the vertical tail.

The data in figure 22 also illustrate another benefit of this automatic trim system. This benefit is that commanded trim roll attitude varies with the level of asymmetric thrust. The pilot is normally instructed to use 5° of roll attitude whenever there is an engine failure, regardless of the airspeed or power level on the operative engine. If the pilot maintains 5° of roll for low differential thrust coefficients with no automatic trim system, the rudder deflection will become reversed as shown in the flight test results. The 5° is only appropriate for full asymmetric power at V_{mc}. Lower power levels on the operative engine or higher airspeeds should require correspondingly lower amounts of roll attitude. This result is exactly what the automatic trim system normally achieves if the pilot lets the rudder pedals float free and controls the heading with the roll attitude.

Dynamic Characteristics

The dynamic response of the airplane to a sudden engine failure during a full-power climb with the controls free is shown in figure 23. Even though there was no feedback of the airplane attitude, the roll-off and nose drop was much less with the automatic trim system on than with the automatic trim system off. The reduction in roll-off was caused by the trim tabs driving the controls in a direction which opposed the roll-off. The automatic trim system for the elevator reduced the tendency of the airplane to pitch down as the engine failed. Actual improvement in the controls-free response is strongly dependent on the control actuation time Δt. The nominal value of 2 sec was used for the run in figure 23.

The dynamic response of the airplane to a sudden reduction of power on the operative engine from a completely stabilized and trimmed flight condition with one engine inoperative and its propeller feathered is shown in figure 24. When the power on the operative engine was reduced, the airplane was no longer trimmed, and it rolled and yawed toward the operative engine. The automatic trim system again reduced the response to the asymmetric power change because of the controls-free movement of the control surfaces. These characteristics should be helpful when maneuvering the airplane for a landing after an engine failure.

Piloted Simulation Maneuvers

Time histories of the airplane responses during a piloted simulated takeoff followed by an engine failure are shown in figure 25(a). In these maneuvers, the pilot was able to maintain better heading and roll control with the automatic trim system on than with the automatic trim system off. There were also fewer oscillations in the attitude; this indicates a lower pilot workload as reflected by the control forces in figure 25(b). However, the automatic elevator trim system evidently caused the pitch attitude to be relatively high, and as a result, the airspeed initially decayed more rapidly with the system on. The larger airspeed decay resulted in a slightly higher initial peak altitude because the total energy (potential plus kinetic) was practically the same for both maneuvers.

The control positions and forces for the same maneuver are shown in figure 25(b). The automatic trim system quickly reduced the control forces as expected, and except for the first second or two after the engine failure, the control surface positions were practically identical. The automatic trim system began changing the trim-tab deflections immediately after the engine failure (fig. 25(c)), which improved total response to the initial airplane divergence. Without the automatic trim system the pilot took from 10 to 15 sec after the engine failure to make a trim-tab change because he was busy maintaining control and feathering the propeller. The manual trim-tab changes were not large enough in the aileron and rudder axes and the pilot was still maintaining substantial control forces in these axes even after 35 sec. (See fig. 25(b).) The manual trim-tab input in pitch was more than adequate and the resulting forces were about the same with the automatic trim system on or off.

In general, the pilots thought the automatic trim system made the airplane easier to control in an engine inoperative condition. In terms of Cooper-Harper pilot ratings, there was an improvement of 2 or 3 pilot rating units over that for the unaugmented airplane, depending on the pilot giving the rating. This improvement was the largest for the takeoff maneuver but the automatic trim system was also beneficial for the landing maneuver. The automatic trim system was beneficial in two basic ways:

(1) it reduced the rate of the initial airplane divergence after an asymmetric thrust change and (2) it reduced the steady-state control forces and practically eliminated the need for manually retrimming the airplane. Although the automatic trim system did not produce a perfectly trimmed condition, the pilots usually did not think it was necessary to manually trim out the small forces which were still present. Apparently, the automatic trim system provided a reasonable balance between system intervention and keeping the pilot "in the loop." In other words, even though it reduced their workload, the pilots did not get the impression that the automatic trim system was taking control of the airplane away from them. The pilot was still in direct control of the primary control surfaces, and the airplane responded to the initial failure in a normal fashion so that there was no mistaking that an engine had failed.

The main detracting characteristic of the automatic trim system was related to the standard technique that light airplane pilots use to identify the correct propeller to feather. Pilots of light twin-engine airplanes are usually taught to identify which engine has failed by associating it with the foot that is not applying the large rudder pedal force required to maintain control of the airplane. (The direction of the rudder pedal input must be instinctive or control of the airplane will be lost immediately.) Thus, if the pilot is not pushing on the left pedal, the left engine has failed. Since the automatic trim system greatly reduced the pedal force required or even slightly reversed it, the time-honored "dead foot—dead engine" mnemonic became meaningless because both feet were essentially "dead." One pilot thought that this confusion was at least partially caused by the lack of yawing motion cues in the simulator. He thought that this confusion would be reduced, if not eliminated, in actual flight where the yawing motion cues would help identify the inoperative engine. In general, however, all the pilots agreed that the cueing lights on the prop controls were needed more with the automatic trim system on than with it off. The cueing lights were used primarily to confirm the pilot's independent determination of which propeller should be feathered. Extended experience with the cueing lights would probably increase the confidence of the pilots in the lights and increase their reliance on them.

Residual force variations. The pilot ratings obtained by varying the residual force parameter while holding the other automatic trim system parameters at their nominal values are shown in figure 26. If the residual force was positive, the initial airplane divergence was larger than for $\widehat{F} = 0$ and steady forces were required to stabilize the airplane in the steady state. If the residual force was negative, the initial airplane response was further suppressed compared with the responses with the nominal zero residual force; but steady forces in the reversed direction were required to stabilize the airplane in the steady state. The primary research pilot gave his best rating for a residual force of −25 percent (fig. 26), whereas the other two pilots preferred the nominal zero residual force. The primary research pilot was apparently more sensitive to the initial engine-failure dynamics, whereas the other two pilots were more sensitive to the steady-state forces. Even with a 25-percent change in the residual force from the nominal value, the pilot rating was still substantially better than the system-off ratings. (See fig. 26.) Thus, the errors shown in figure 10 for the flight test measurements do not preclude the effectiveness of the automatic trim-tab system with a single slipstream sensor.

Response times. The handling qualities were not as sensitive to the response time as might be expected. This insensitivity is the reason a rather coarse (0.5, 2, 8, or 32 sec) division of response time was used in this study. The fact that the automatic trim was an open-loop system probably explains the insensitivity. The pilot had to always supply the stability for the airplane, and the response time mainly affected the amount of time he had to hold the unaugmented control forces. Evidently, it did not matter a lot whether he had to hold the forces 2 or 3 sec because he was busy stabilizing the airplane immediately after the engine failure. When the automatic trim system response time Δt was varied while holding the other three automatic trim system parameters at their nominal values, the pilots generally preferred the fastest response times of 0.5 and 2 sec. The faster response times reduced the initial divergence and did not affect the steady-state control forces. The only possible drawback of the fastest response time was that it tended to take the pilot out of the loop somewhat so that he got the impression that he was no longer the primary determinant of what the airplane was doing. One pilot, therefore, rated the 0.5-sec response time as slightly less desirable than the 2-sec response time. (See fig. 27.)

The faster response times obviously require more capability in the trim-tab motor. Even the nominal 2-sec response is many times faster than that for currently used trim motors. The faster response times also pose problems in certification of the failure modes of the automatic trim system. (See ref. 14.) A runaway trim motor can cause large disturbances to the airplane, especially in the pitch axis, and must be detected and corrected quickly. However, as aircraft avionics systems evolve toward more sophisticated digital logic, failure test and correction features should be capable of controlling a runaway trim motor with an acceptable disturbance to the airplane.

Minimum trim speed variations. When the minimum engine-inoperative trim speed V_p was increased above the nominal value, according to the pilots' verbal comments, there was relatively little degradation in the handling qualities until $V_p = 100$ or 110 knots. The handling qualities with $V_p = 90$ knots were judged to be about the same as with the nominal value of $V_p < V_s$. Even though both the aileron and rudder trim tabs were less powerful than the nominal automatic trim system, the pilot could not readily tell the difference between the 90-knot automatic trim system and the nominal automatic trim system. The airspeed rarely went below 90 knots; therefore, the automatic trim system was able to effectively zero all the forces once the propeller was feathered. When $V_p = 120$ knots, the handling qualities were judged to be clearly inferior to those with the nominal value of $V_p < V_s$. However, the handling qualities were still better than with no automatic trim system. The engine failures for the takeoff maneuvers generally occurred at an airspeed of 100 knots; therefore, the 120-knot automatic trim system was unable to relieve all the control forces due to the asymmetric thrust. After the propeller was feathered and the value of $V_{Y,se}$ of 109 knots was established, however, the forces were very nearly trimmed.

The actual pilot ratings, shown in figure 28, indicate that there was a substantial degradation (1 pilot rating unit) in the handling qualities even when $V_p = 90$ knots. This inconsistency with the verbal comments may be because the numerical pilot ratings for the nominal system were not taken at the same time that the other ratings were taken. It is believed that the pilots' verbal comments, which were given previously, give the more accurate impression of the effect of the minimum trim speed V_p on the handling qualities. In either case, the minimum trim speed or the trim-tab authority is a very important determinant of automatic trim system performance.

Trimmed roll attitude variations. The handling qualities were judged to be relatively unaffected by the values of ϕ_c tested except for the extreme values. (See fig. 29.) With the automatic trim system designed for $\phi_c = 10°$, the pilots felt that this roll angle was excessive and they began to oppose the roll. This reversed roll control input felt very unnatural to the pilots and as a result they rated this particular automatic trim system as much worse than the nominal automatic trim system and possibly worse than no automatic trim system. Its only good feature seemed to be the large and rapid aileron input which limited the initial roll-off after the engine failure. The undesirable characteristics of this automatic trim system were related only to its effect on engine-inoperative control and not the impact of the roll angle on single-engine climb performance. For this part of the tests, the airplane drag was arbitrarily adjusted such that the climb for the $\phi_c = 10°$ automatic trim system was the same as that for the nominal automatic trim system. This approach allowed the evaluation to focus on the control aspects only.

When $\phi_c = -1°$, the pilots thought the handling qualities were not quite as good as with either the nominal value of 3° or with $\phi_c = 5°$. There seemed to be some tendency of the pilots to still try to roll into the operative engine for $\phi_c = -1°$. When they tried this, the rudder control force became slightly reversed and as a result the automatic trim system was given a somewhat degraded pilot rating.

In summary, it seemed that 10° of roll was excessive, even if the vertical tail did not stall and the degraded performance was neglected. A value of ϕ_c between 3° and 5° was acceptable from both control and performance standpoints.

Engine-inoperative landings. All three pilots gave the automatic trim system a 2-pilot-rating-unit better rating than the unaugmented airplane for the misjudged approach and landing maneuver. The automatic trim system kept the airplane in trim for all power levels on the operative engine and made retrimming unnecessary throughout the maneuver. The automatic trim system also suppressed the initial transients after an increase or decrease in power on the operative engine.

The automatic trim system was of almost negligible benefit for the normal engine-inoperative landing. The VFR, no-wind conditions allowed the pilots plenty of time to make slow power changes and make easy landings on the long runway (11 500 ft).

Single-axis systems. As stated earlier, the nominal automatic trim system really consisted of three separate systems in the pitch, roll, and yaw axes. When only one axis at a time was activated, the pilots in general did not find any one axis markedly more beneficial than either of the other two. Each single axis provided some benefit, but the benefit of one axis alone never approached the combined benefit of all three axes working simultaneously. For example, the rudder system alone was not nearly as effective as the combined automatic trim system.

It was found that proper design of the elevator system was very important. It was desirable to have some pitch-down trim change after the engine failure to help eliminate the natural tendency to let the airspeed decay to dangerously low values. The unaugmented airplane in this simulation had too large a pitch-down trim change; thus, the automatic trim system was designed to eliminate about half of this change as described earlier. If the unaugmented airplane had not had the pitch-down trim change, it would have been very desirable (and easy) to design the automatic trim system to produce at least a mild pitch-down.

Conclusions

A simulation study has been conducted to investigate an automatic trim system concept designed to improve the flying qualities of light twin-engine airplanes after an engine failure. The automatic trim system drove the rudder, aileron, and elevator trim tabs as an open-loop function of differential thrust coefficient. The control law was derived under the premise that differential thrust coefficient is a function of measurements of differential slipstream dynamic pressure. The primary conclusions of the study are as follows:

1. The automatic trim system was found to be beneficial for coping with both sudden engine failures and for extended post-engine-failure maneuvering when the power level on the operative engine must be varied.

2. The improvements provided by the automatic trim system are due primarily to suppression of the initial transients after a change in the asymmetric power level and by reductions in the static control forces after the airplane was stabilized.

3. The automatic trim system seemed to strike a reasonable balance between automatic trim system intervention and keeping the pilot in the loop.

4. The research pilots rated the flying qualities of the airplane with the automatic trim system to be 2 to 3 pilot rating points better than those of the basic airplane for a maneuver involving an engine failure immediately after takeoff.

5. The automatic trim system substantially improved the handling qualities, even with system errors of 25 percent.

6. The automatic trim system response times may pose problems in the certification of the failure modes.

7. The reduced rudder pedal forces with the automatic trim system on made the task of identifying the correct propeller to feather more difficult. Also, the lack of yawing motion cues in this simulation may have complicated the task of identifying the correct propeller.

8. Flight test measurements of the propeller slipstream indicate that the proposed control law is viable.

9. The minimum trim speed should be as low as possible. For an automatic trim system using trim tabs rather than powered actuators, this requirement means that the trim tabs should have as much authority as possible.

10. The pitch axis system of the automatic trim system should be designed to produce at least a mild pitch-down trim change after an engine failure. Such a trim change is needed to help eliminate the natural tendency to let the airspeed decay to dangerous levels for an engine failure after takeoff.

11. The aileron can be used to control the amount of bank into the operative engine and to boost the apparent effectiveness of the rudder in controlling engine-inoperative asymmetries. However, the practical limits of this boost were not investigated in this study because vertical tail stall effects were not modeled.

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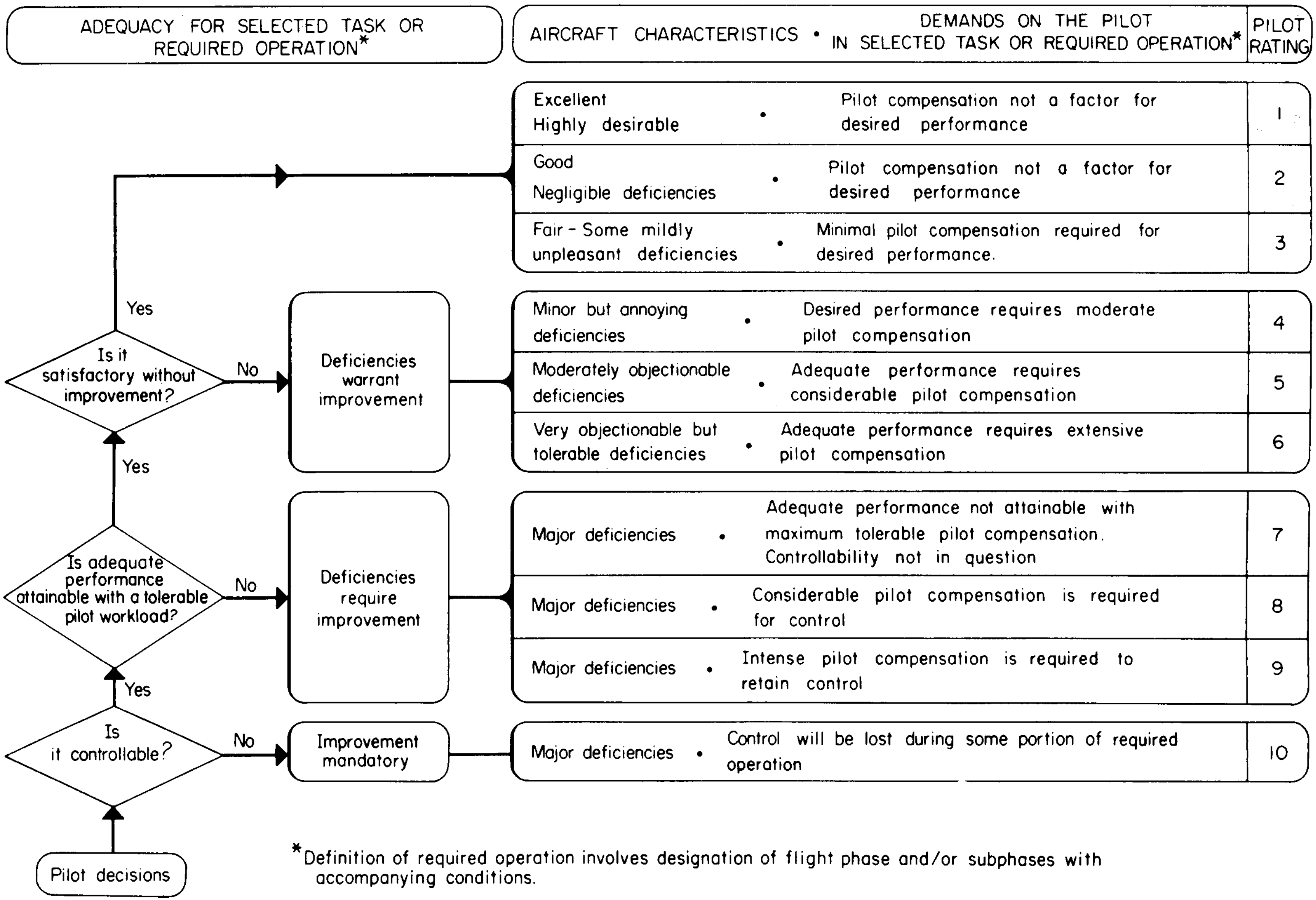
Table I. Handling Qualities Rating Scale



*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

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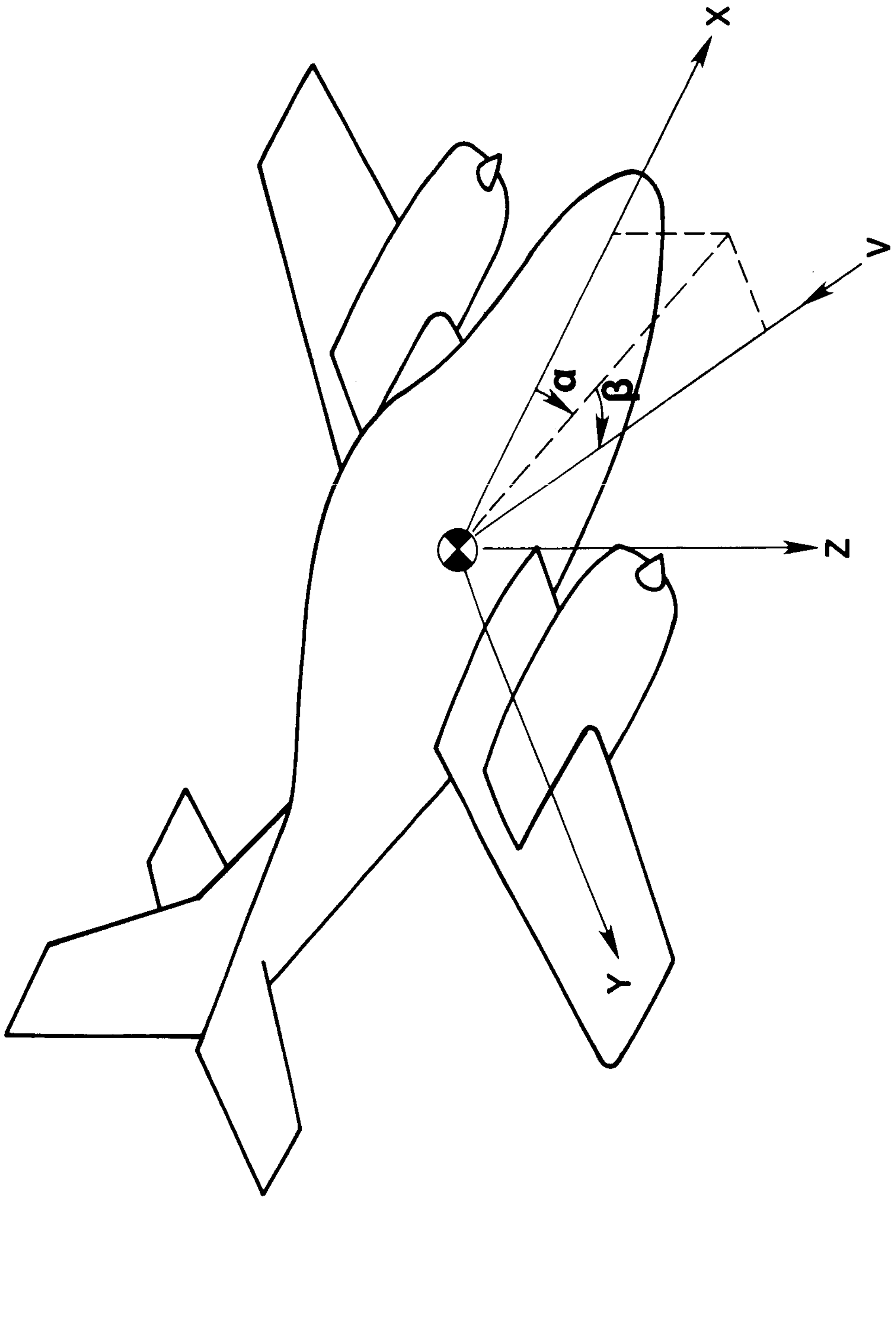

Figure 1. Axis system.

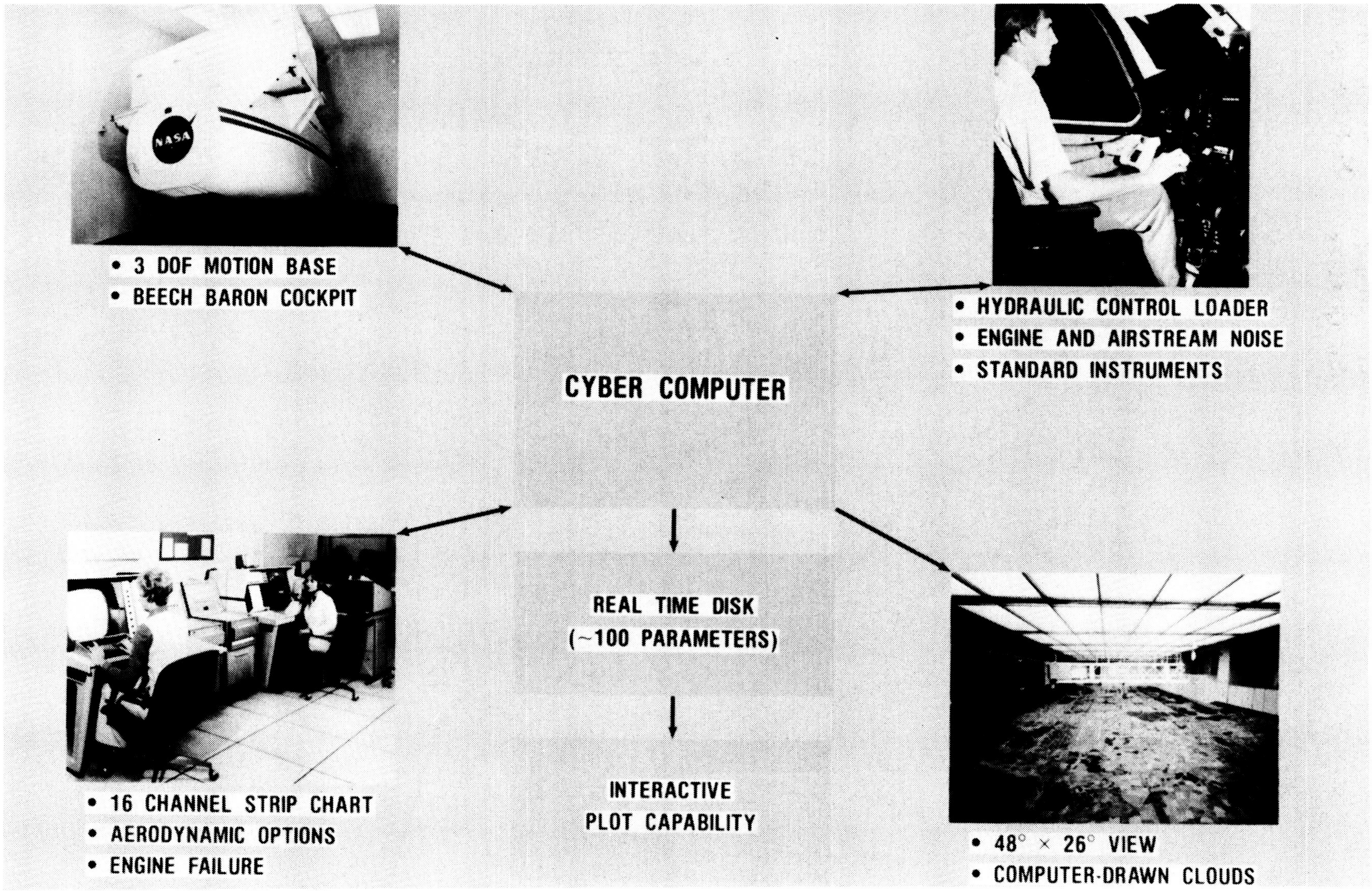

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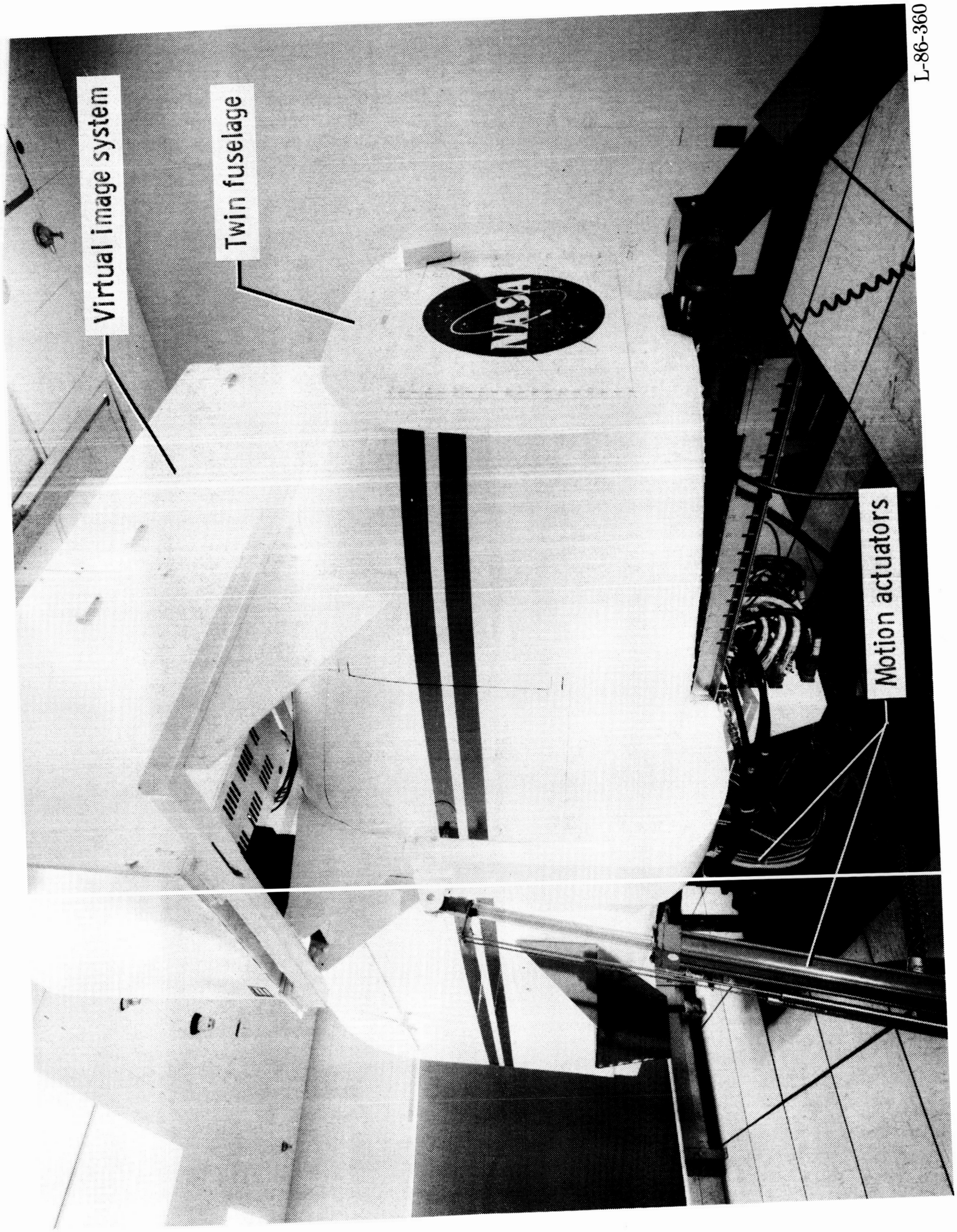
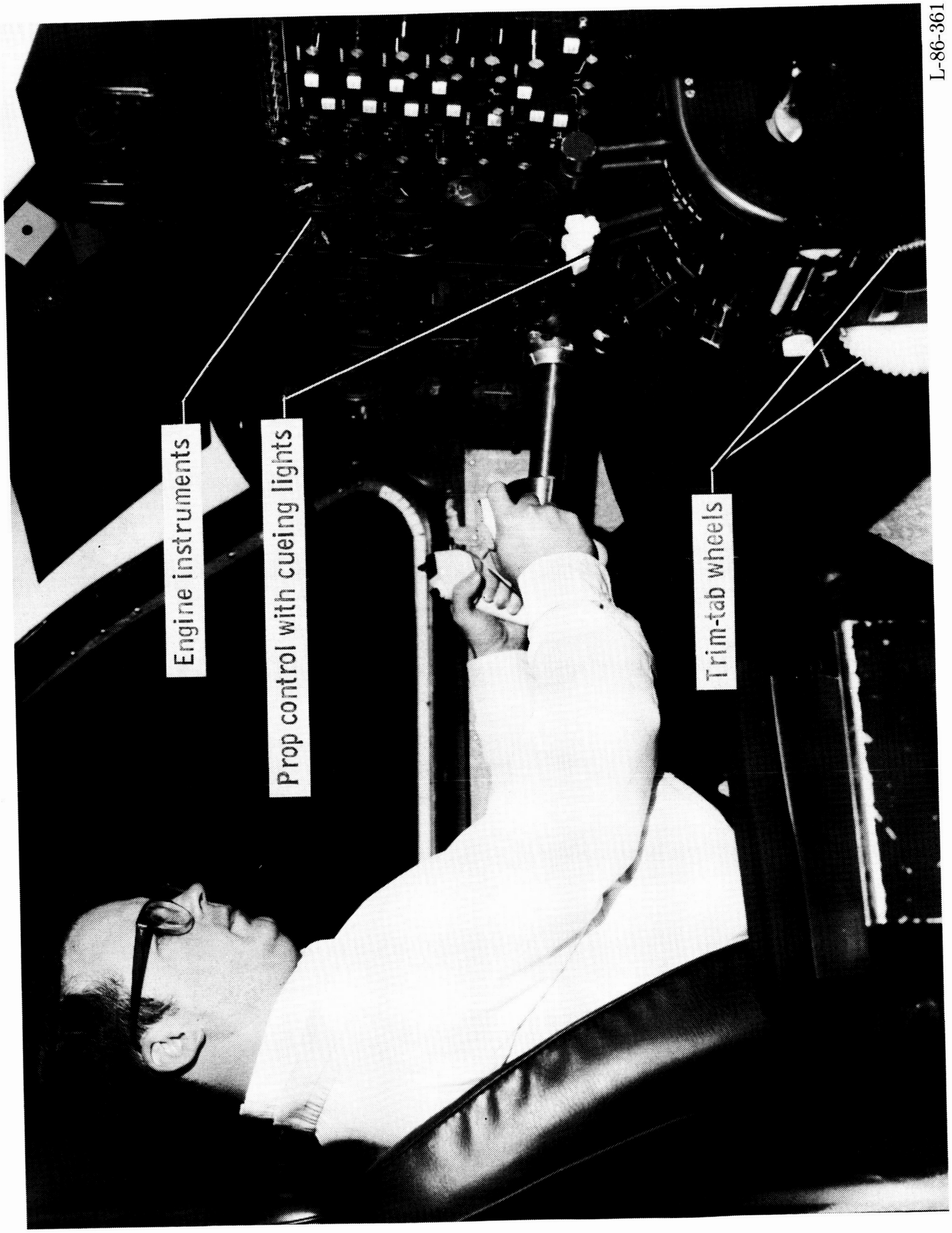
Figure 2. Simulation system used in investigation.



L-86-360

Figure 3. Three-degree-of-freedom motion base and virtual image system.



L-86-361

Figure 4. Simulation cockpit with instruments and controls.

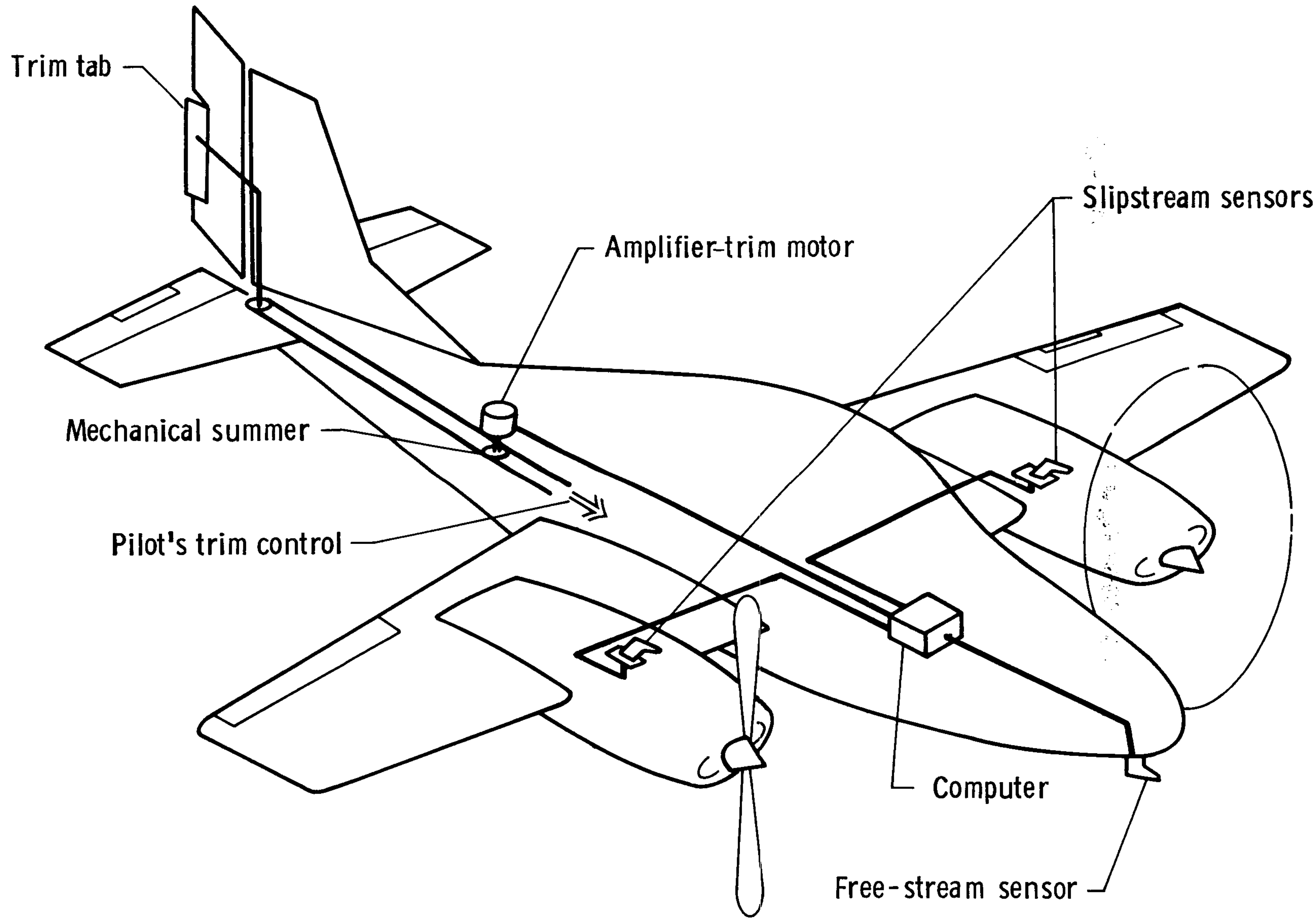


Figure 5. Conceptual sketch of automatic trim system. Elevator and aileron systems are not shown.

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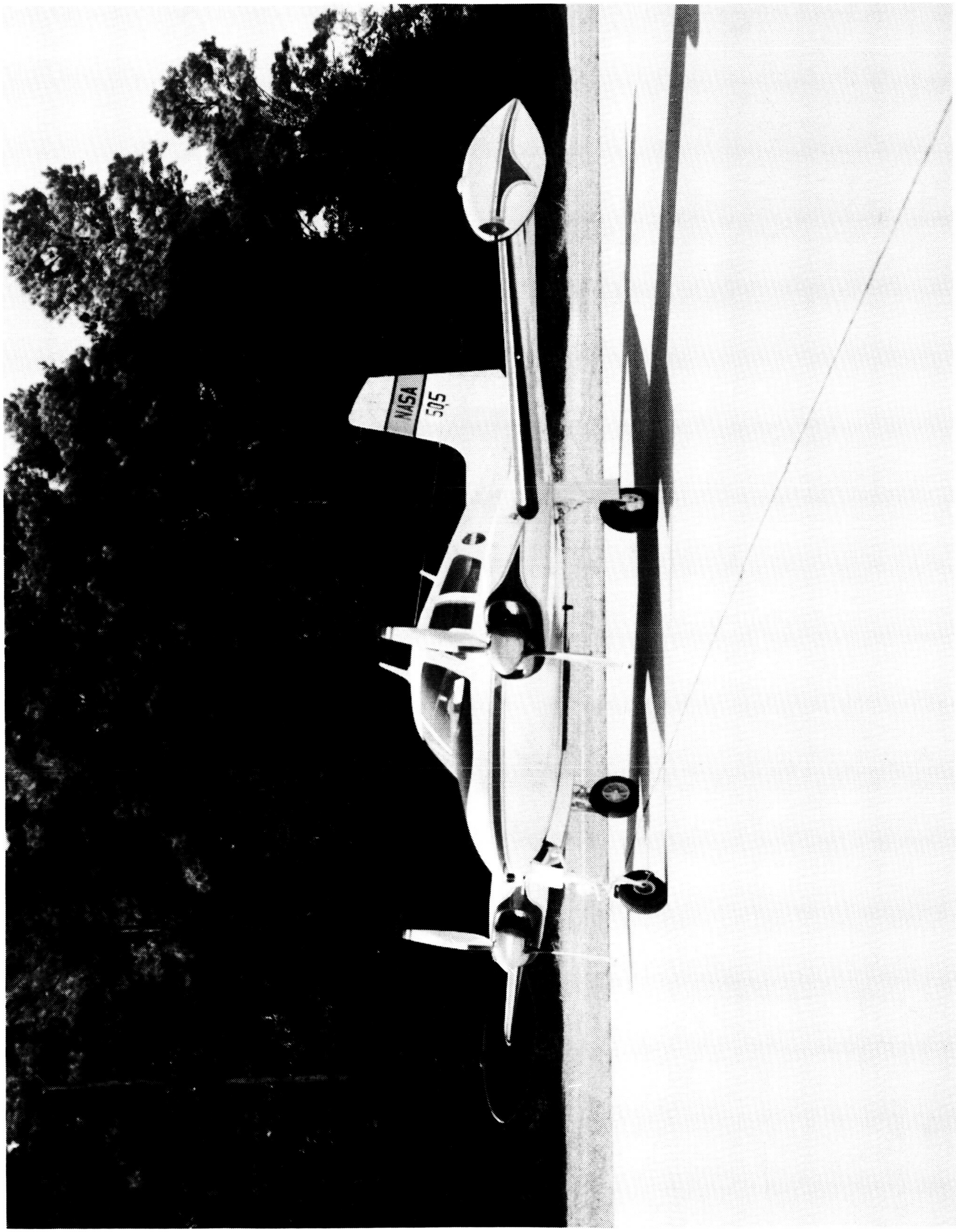

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Figure 6. Airplane used in flight tests.

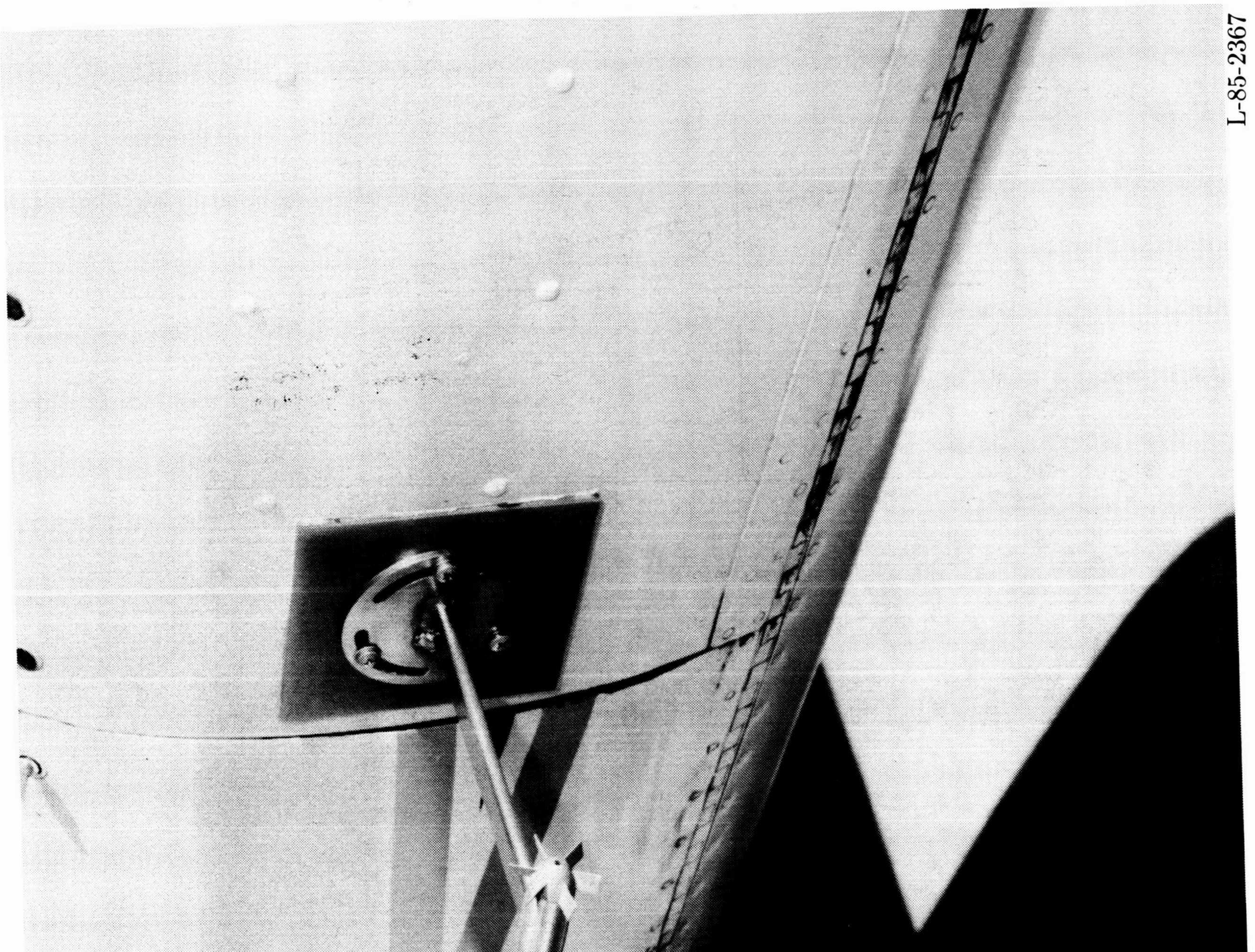

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Figure 7. Anemometer used to measure slipstream velocities.

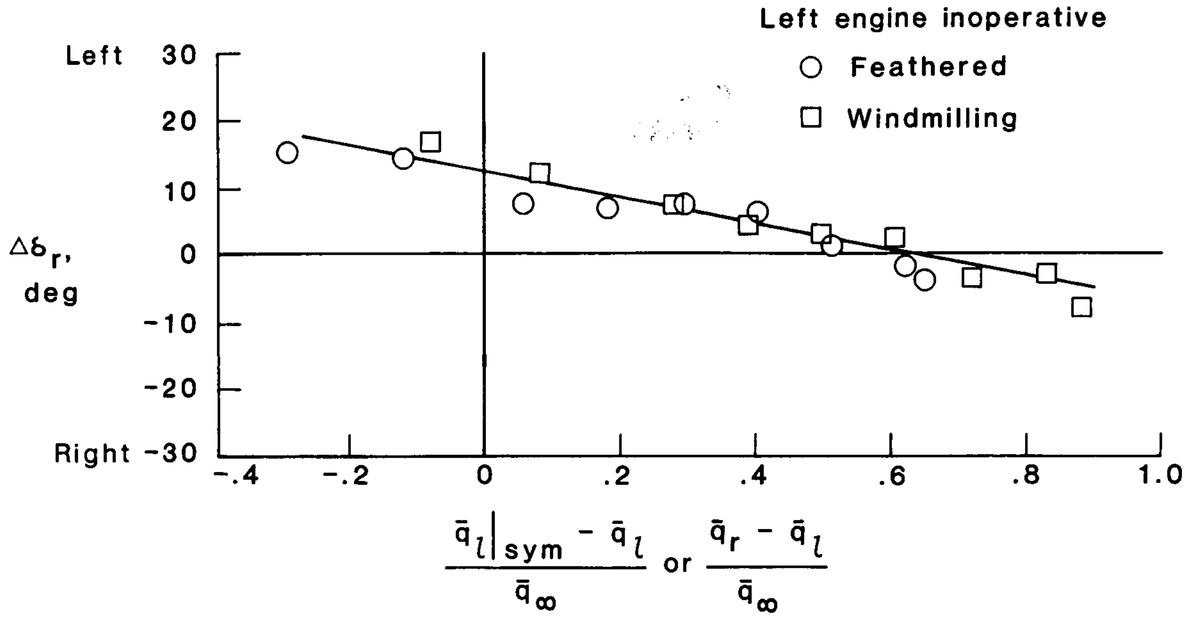


Figure 8. Variation of trimmed rudder position with slipstream dynamic-pressure parameter determined in flight tests. Indicated airspeed, 90 knots; density altitude, 6000 ft; $\phi = 5°$.

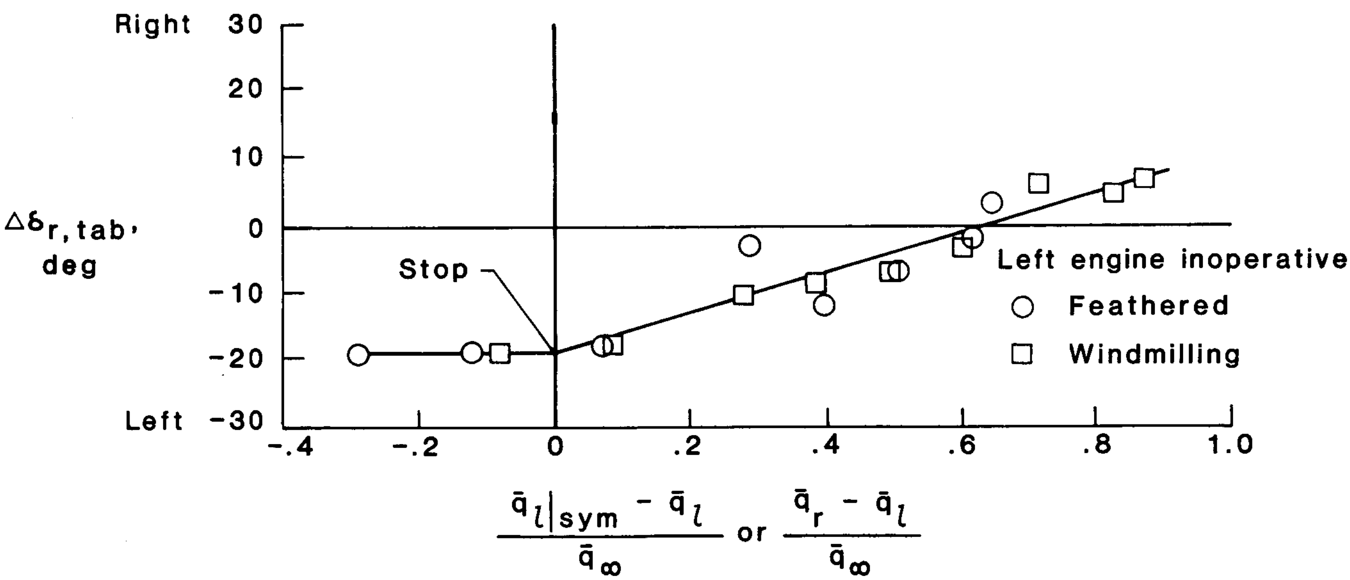


Figure 9. Variation of trimmed rudder trim-tab position with slipstream dynamic-pressure parameter determined in flight tests. Indicated airspeed, 90 knots; density altitude, 6000 ft; $\phi = 5°$.

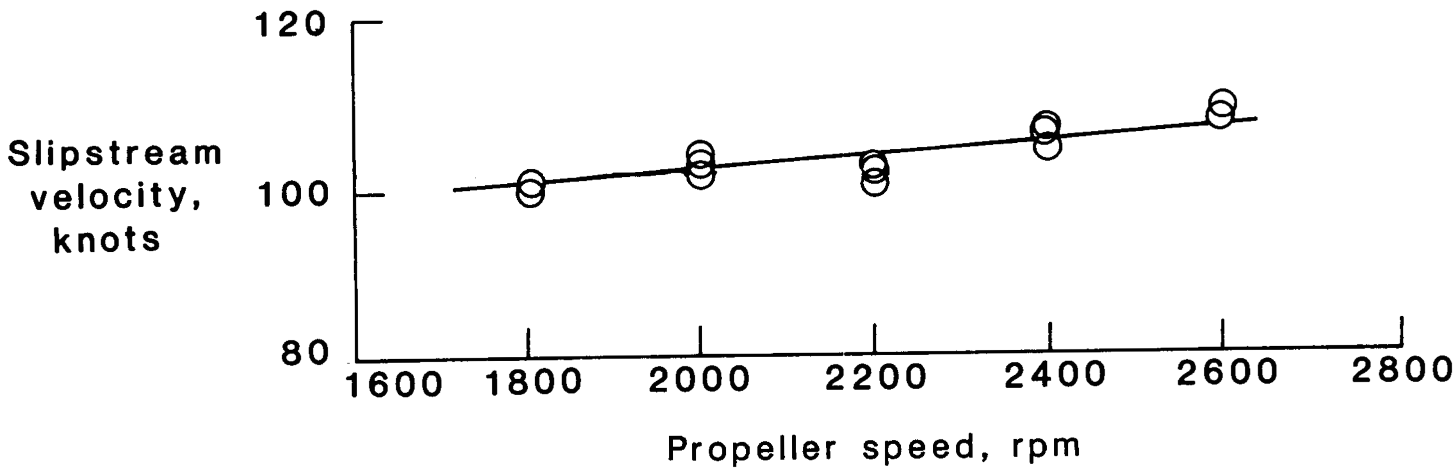


Figure 10. Effect of propeller speed (blade angle) on propeller slipstream velocity at constant total thrust as determined in flight tests. Power for level flight: Indicated airspeed, 90 knots and density altitude, 6500 ft.

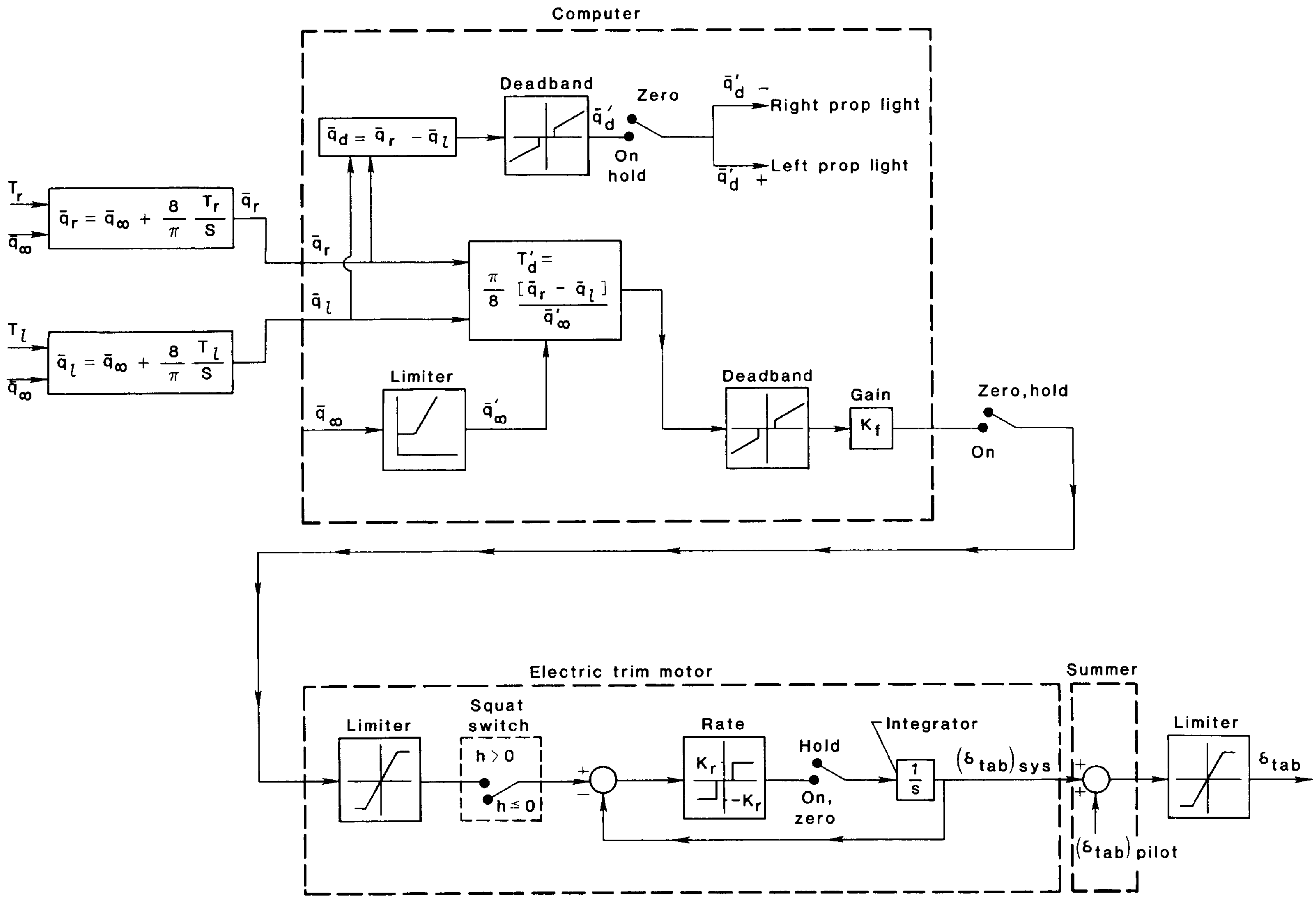
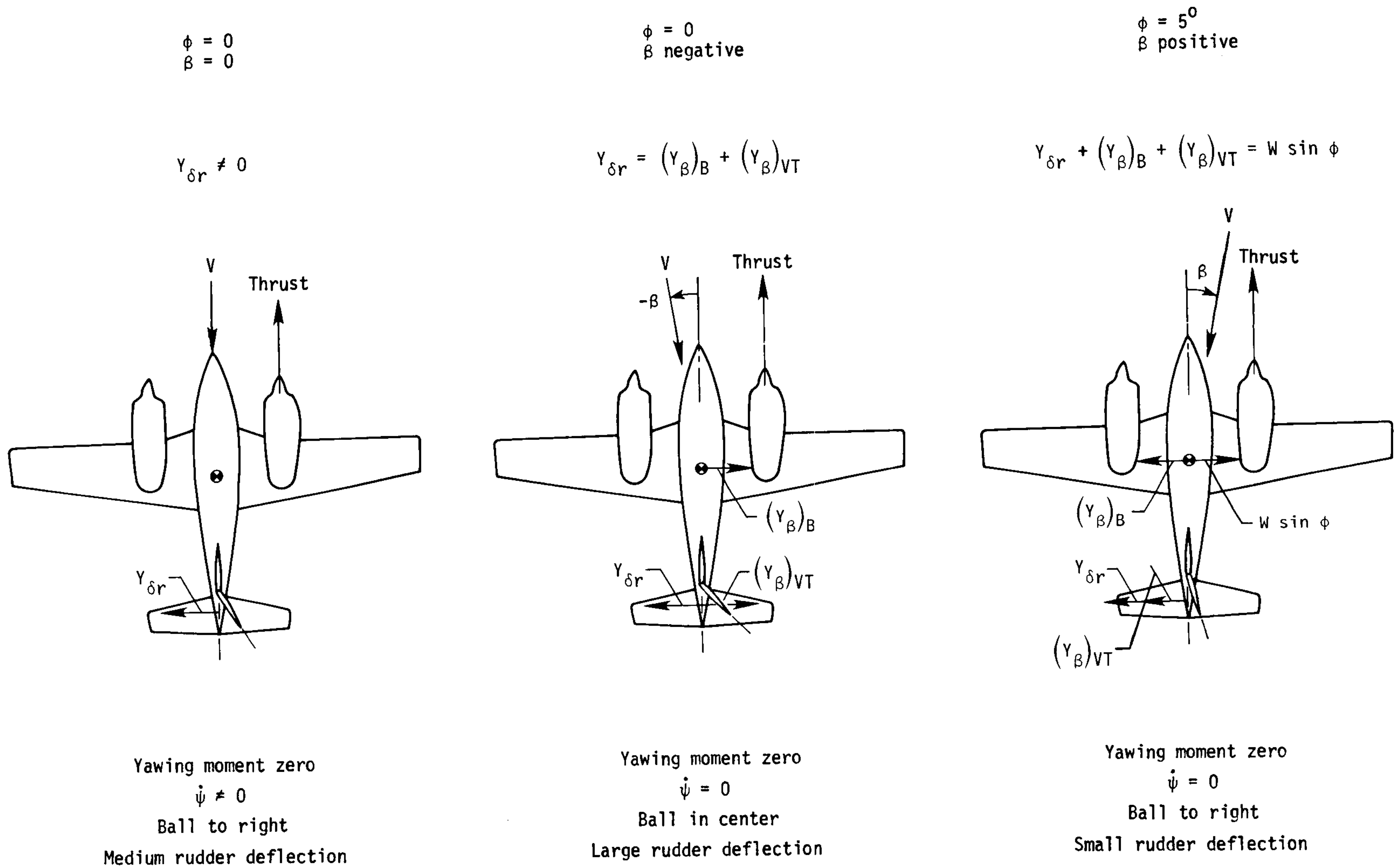


Figure 11. Block diagram of simulated automatic trim system.



(a) Sideslip and roll attitude maintained at zero.

(b) Roll attitude and heading rate maintained at zero.

(c) Roll attitude maintained at 5° and heading rate maintained at zero.

Figure 12. One-engine-inoperative control strategies.

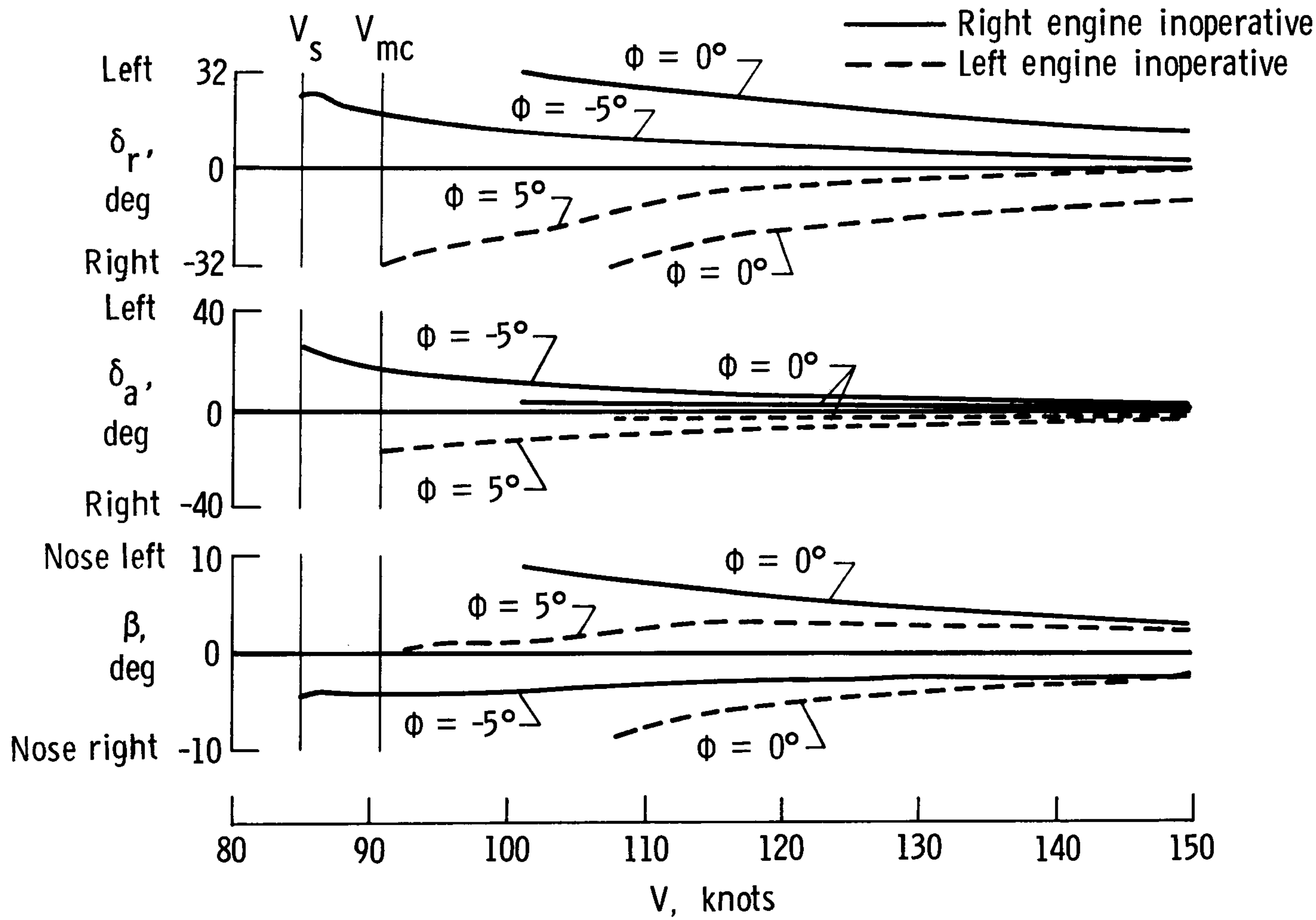


Figure 13. One-engine-inoperative characteristics with propeller windmilling on inoperative engine.

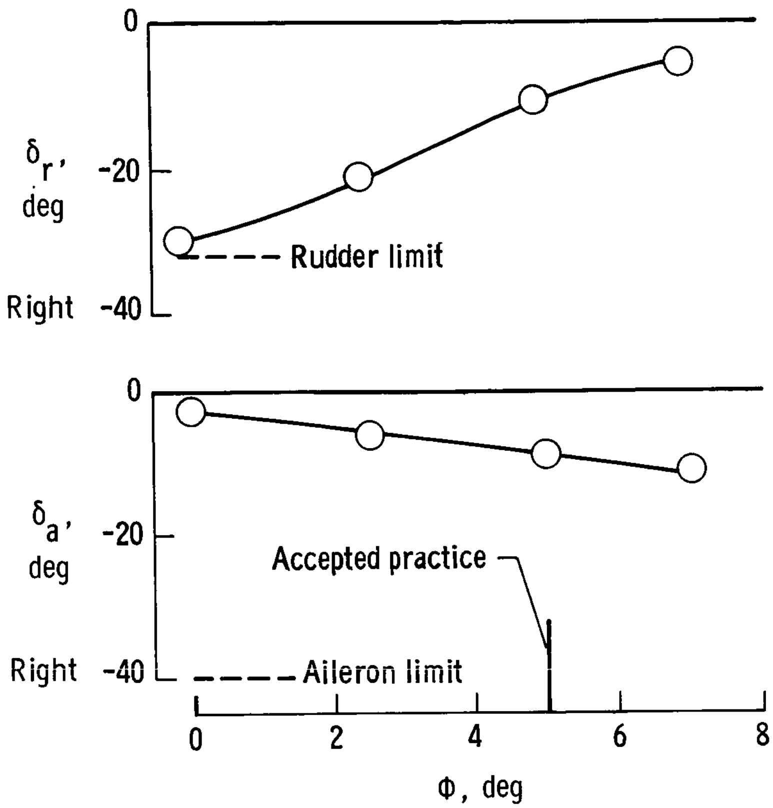


Figure 14. Effect of roll attitude on control surface positions required to stabilize flight. Left engine inoperative and propeller feathered; $V = 109$ knots.

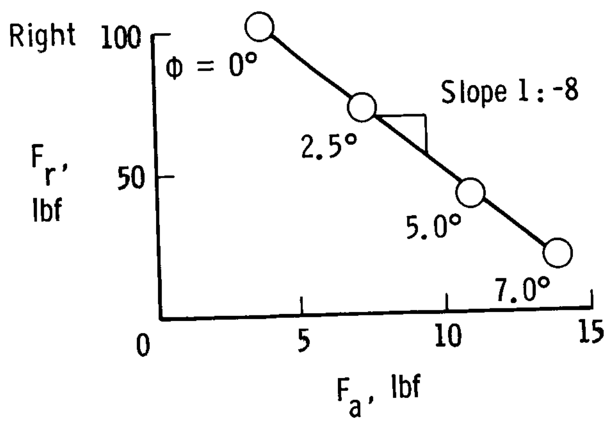


Figure 15. Reduction in pedal force required to stabilize flight as lateral wheel force is increased. Left engine inoperative and propeller feathered; $V = 109$ knots.

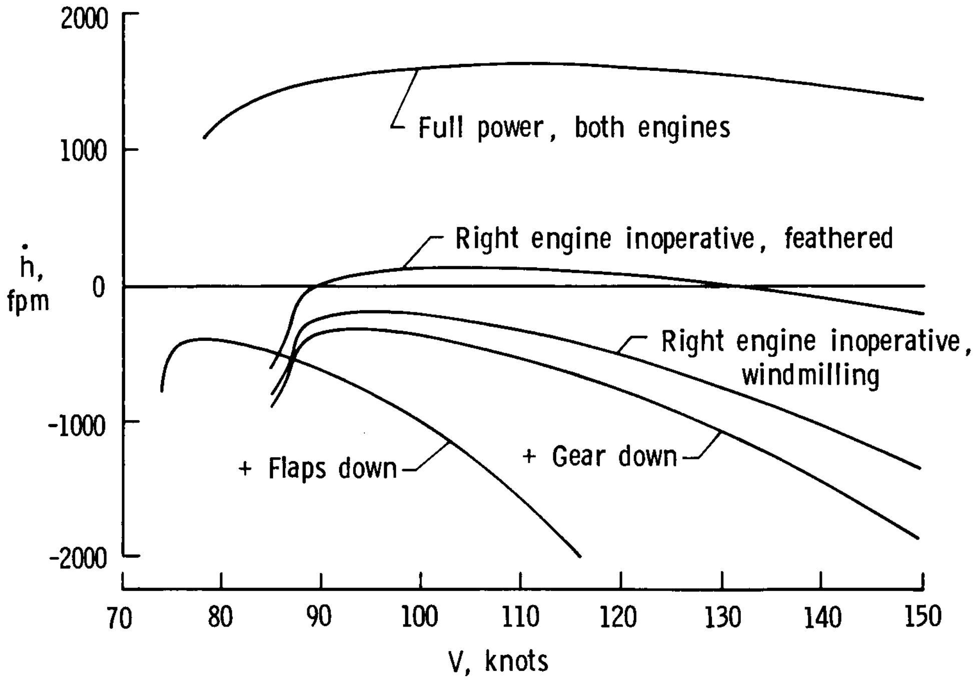


Figure 16. Climb performance for selected configurations of baseline simulated airplane. $\phi = 0°$.

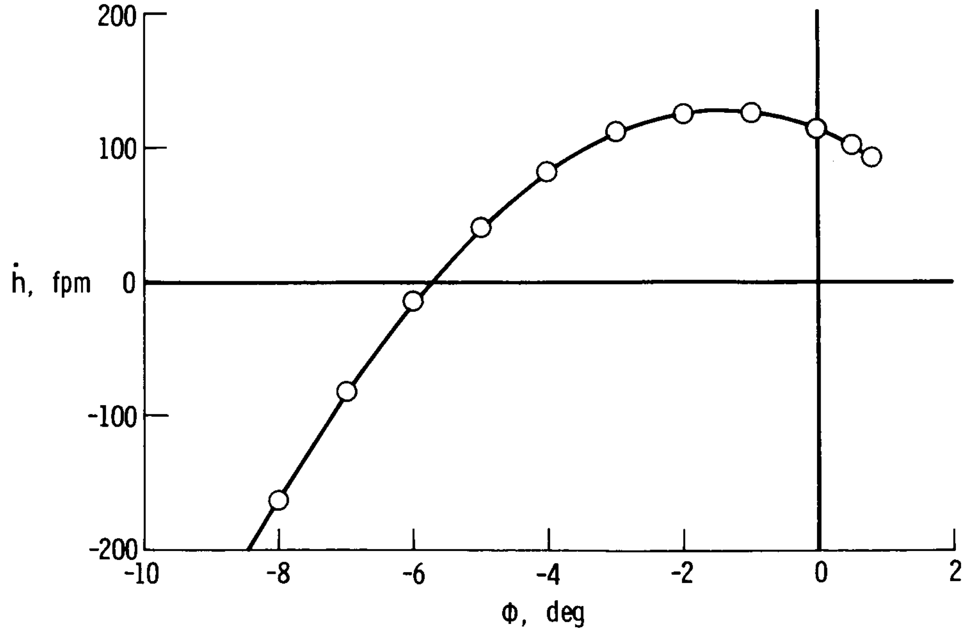


Figure 17. Effect of roll attitude on climb performance with right engine inoperative and right propeller feathered. $V = 109$ knots.

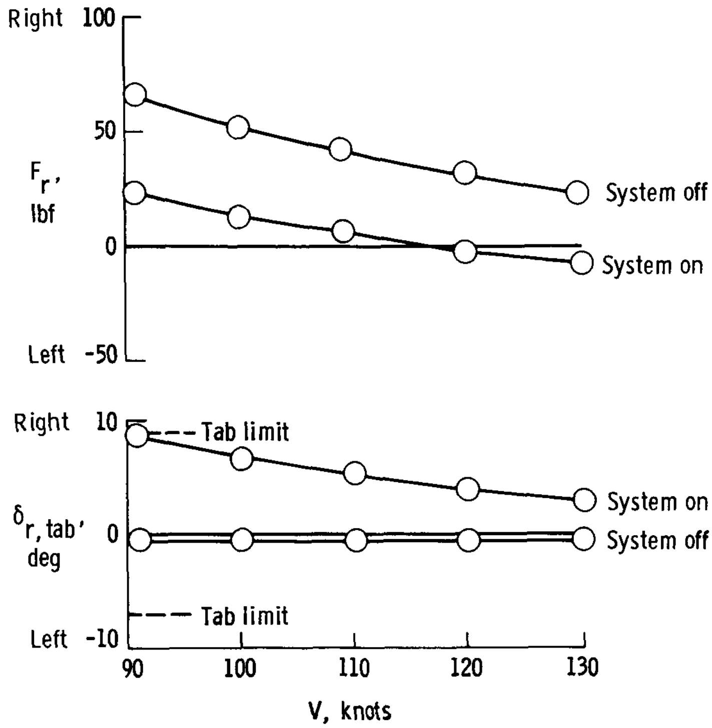


Figure 18. Effectiveness of automatic trim system in reducing pedal forces required to stabilize flight. Left engine inoperative and propeller feathered; $\phi = 5°$; $\hat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

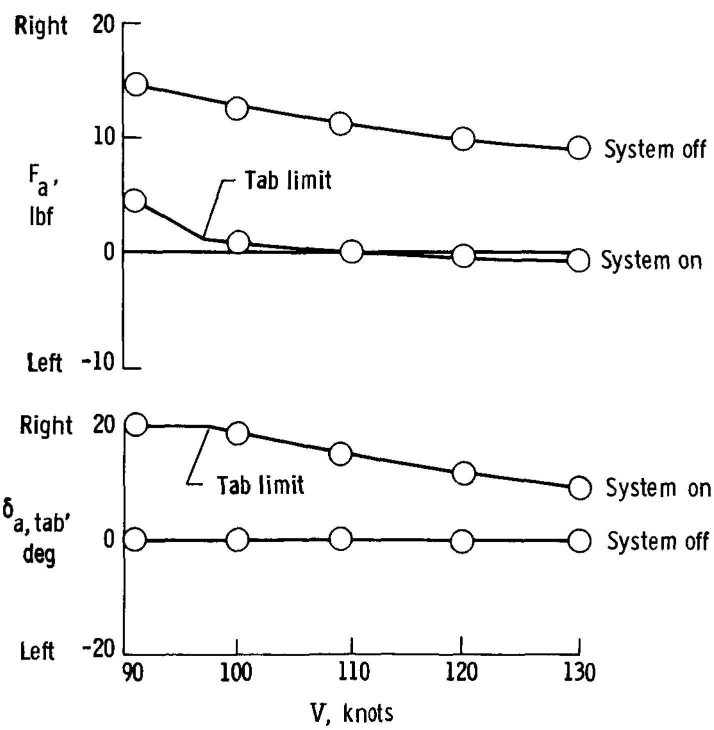


Figure 19. Effectiveness of automatic trim system in reducing lateral wheel forces required to stabilize flight. Left engine inoperative and propeller feathered; $\phi = 5°$; $\hat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

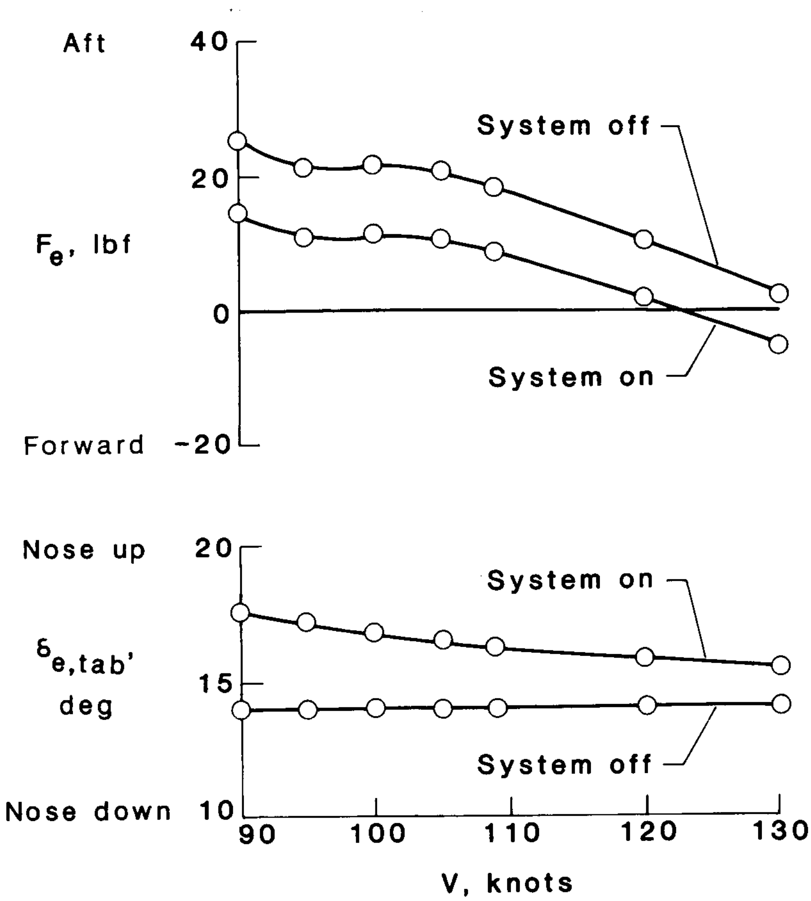


Figure 20. Effectiveness of automatic trim system in reducing longitudinal wheel forces. Initial trim tab set to make control force zero with full symmetric power at 109 knots; right engine inoperative, propeller feathered; $\phi = -5°$; $\widehat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

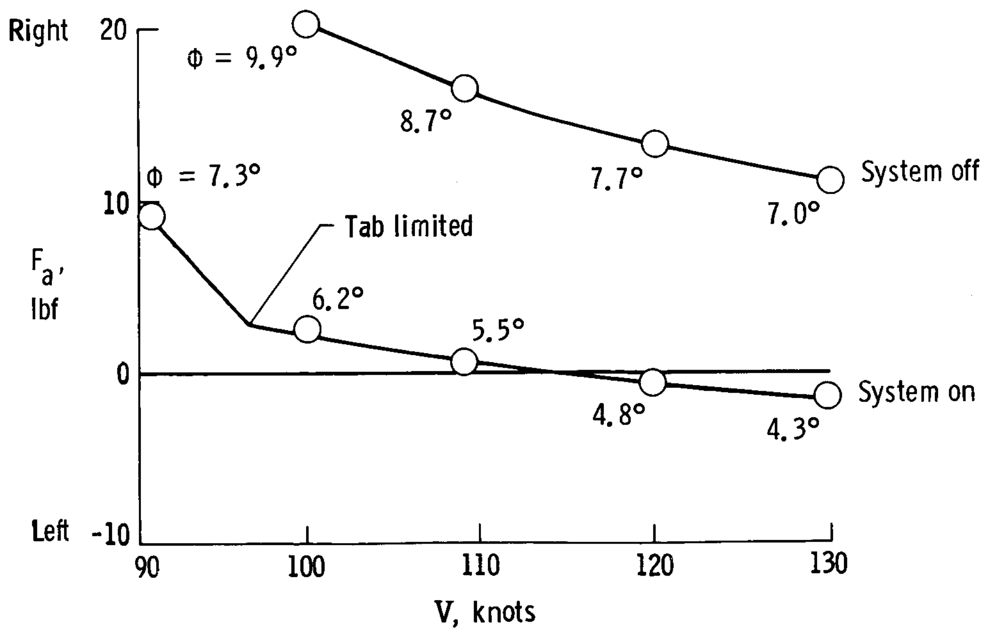


Figure 21. Effectiveness of automatic trim system in reducing lateral wheel forces required to stabilize flight with rudder pedals floating free ($F_r = 0$). Left engine inoperative and propeller feathered; $\widehat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

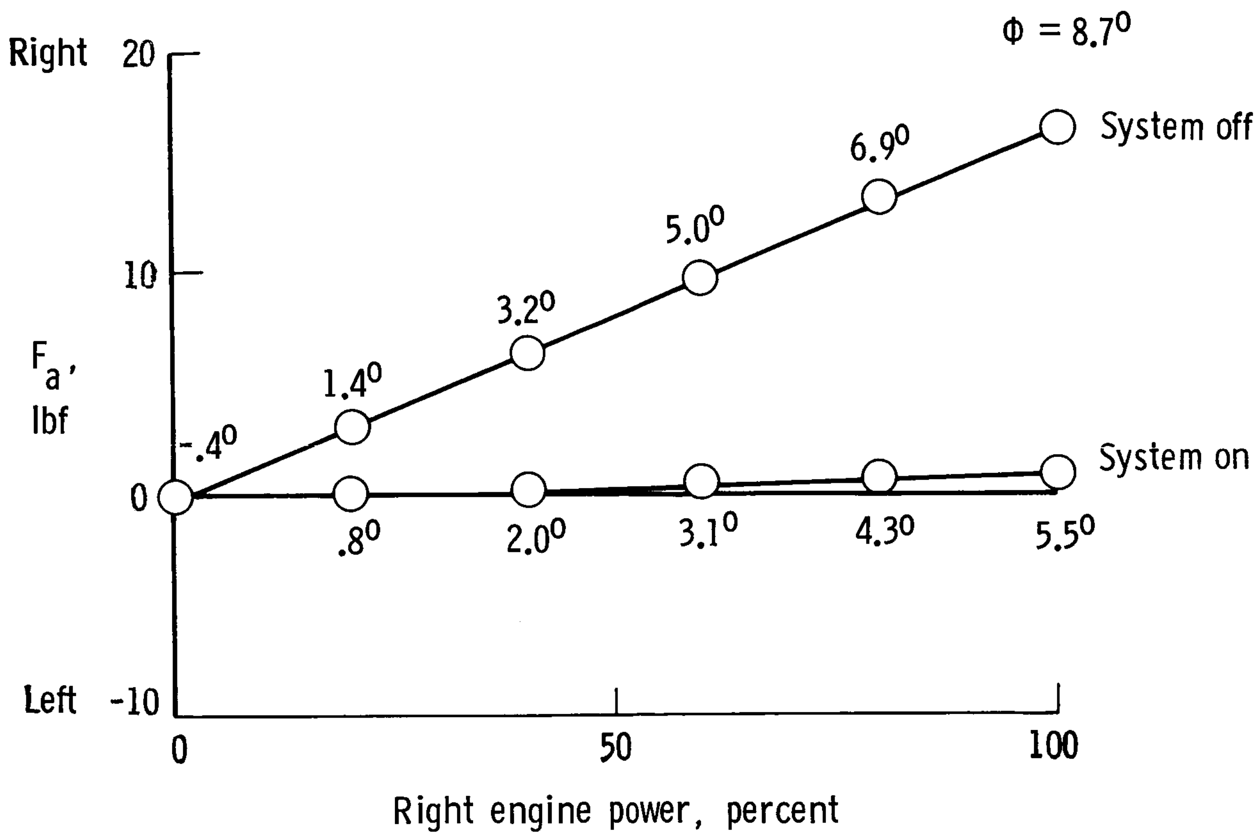


Figure 22. Effect of right engine power on lateral wheel forces required to stabilize airplane. Left engine inoperative and propeller feathered; $V = 109$ knots; rudder pedals floating free ($F_r = 0$); $\hat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

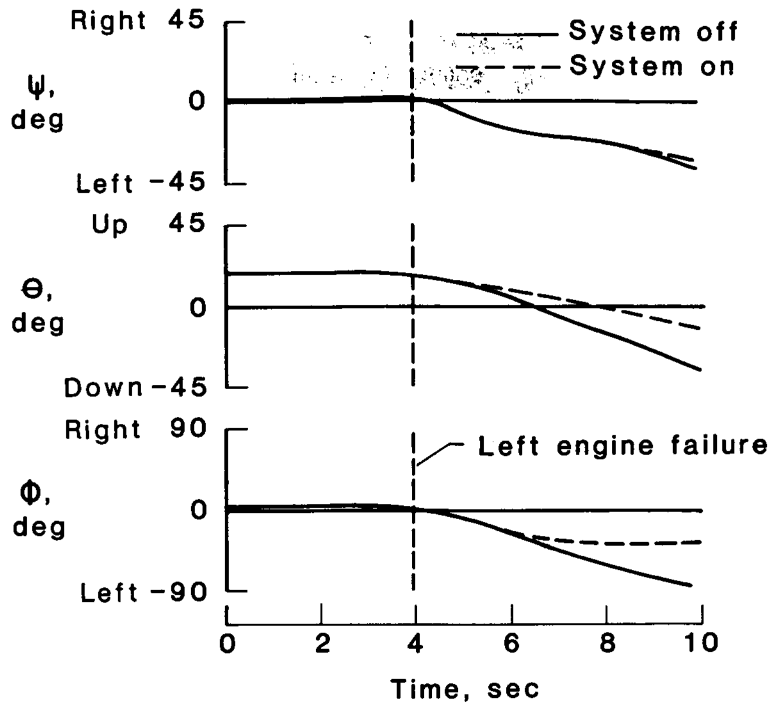


Figure 23. Effect of automatic trim system on airplane dynamics with controls free following an engine failure in a full-power climb. $\widehat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

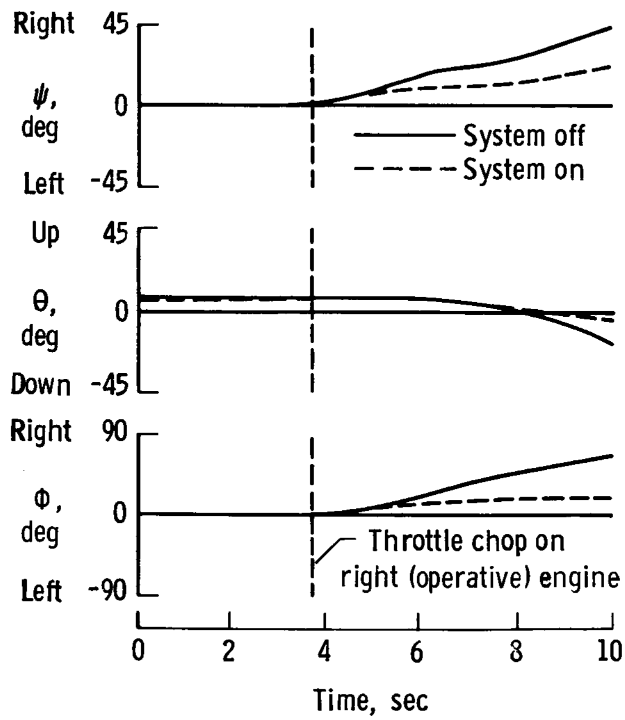
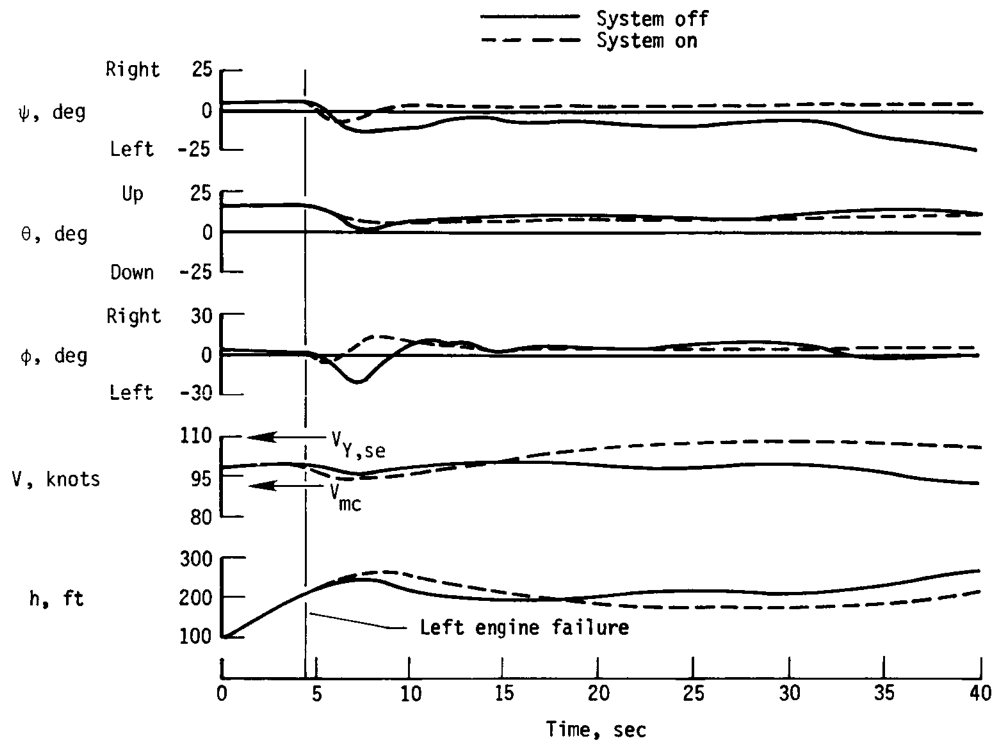
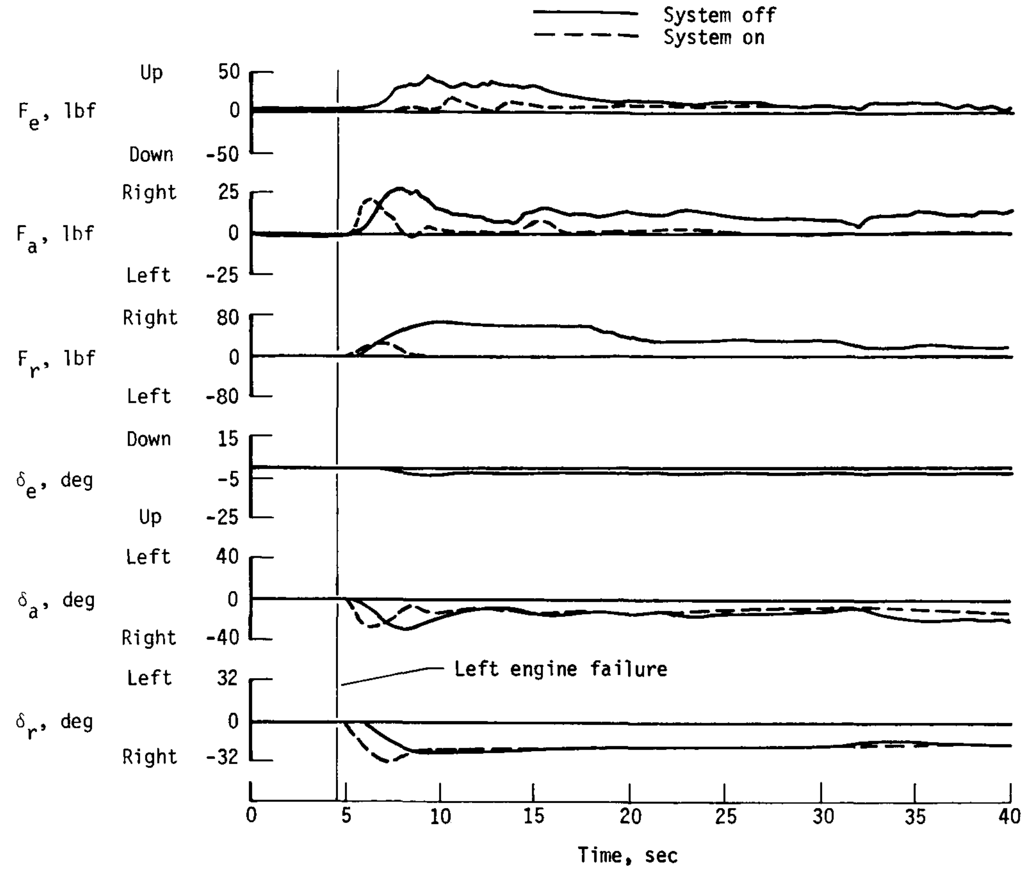


Figure 24. Effect of automatic trim system on airplane dynamics following power reduction on operating engine with controls free. Left engine inoperative and propeller feathered; $\widehat{F} = 0$; $\Delta t = 2$ sec; $V_p = 100$ knots; $\phi_c = 5°$.

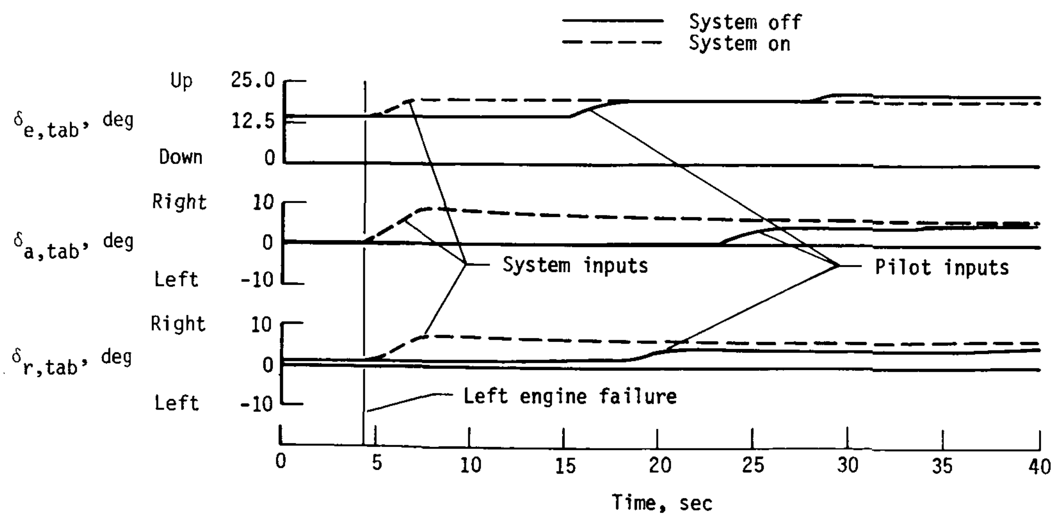


(a) Airplane response.

Figure 25. Comparison of time histories of takeoff maneuver with automatic trim system on and off. Gear and flaps retracted.



(b) Control forces and positions.



(c) Trim-tab positions.

Figure 25. Concluded.

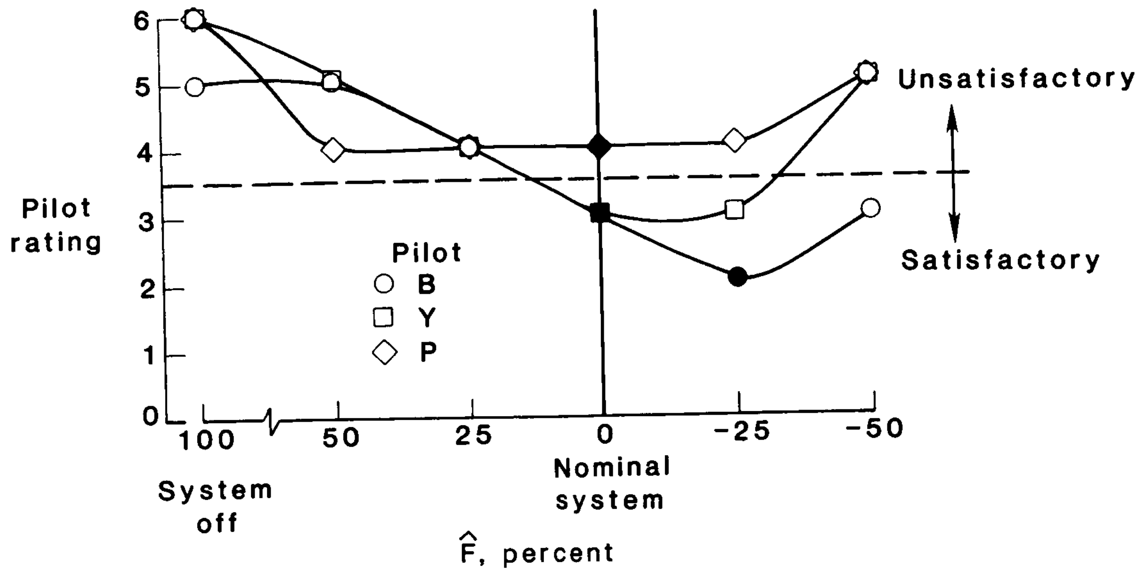


Figure 26. Handling qualities sensitivity of residual control force parameter. Solid symbols indicate best values.

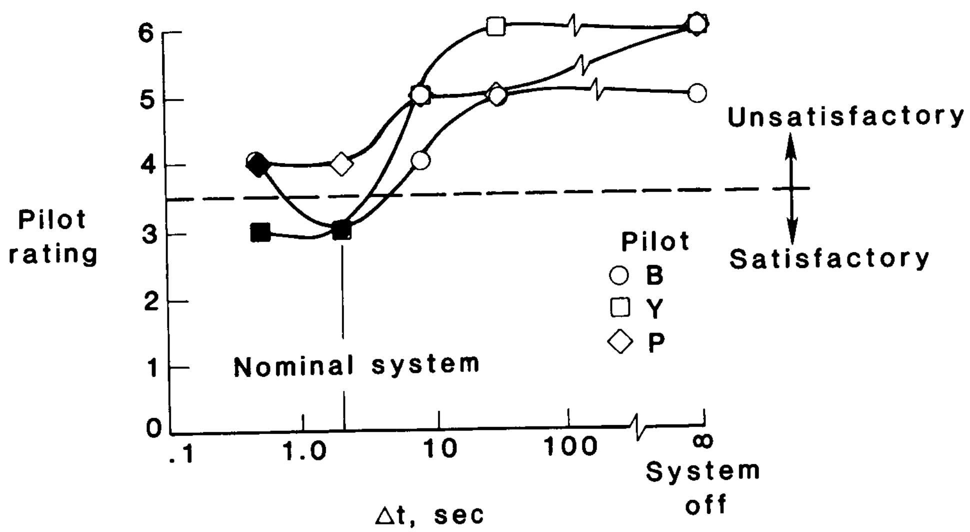


Figure 27. Handling qualities sensitivity to response time. Solid symbols indicate best values.

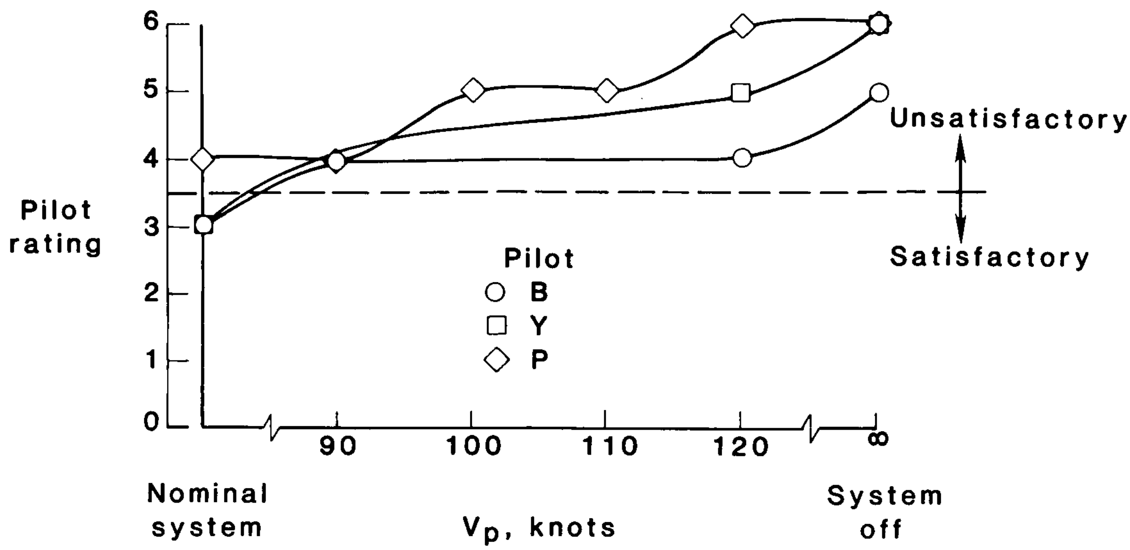


Figure 28. Handling qualities sensitivity to minimum engine-inoperative trim speed.

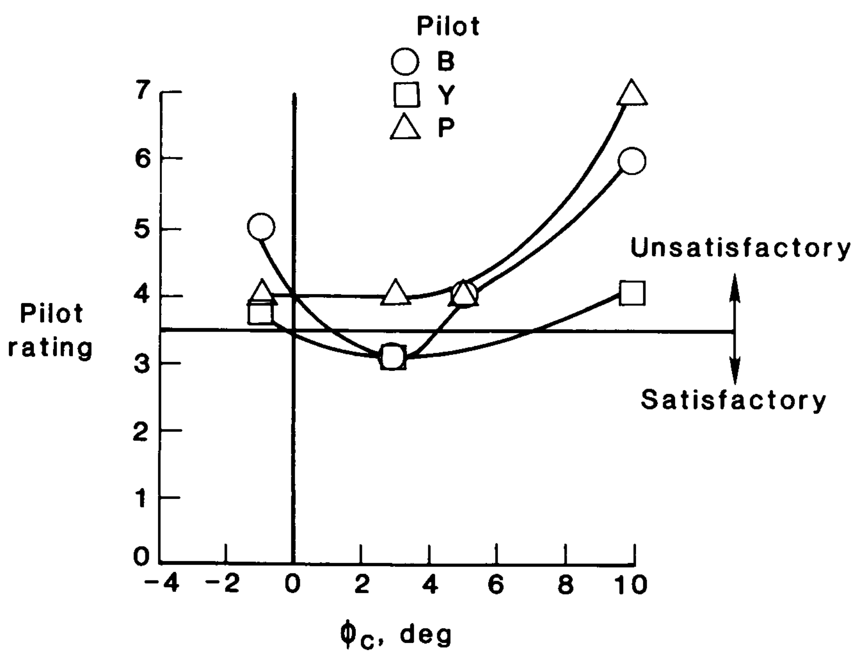


Figure 29. Handling qualities sensitivity to commanded roll attitude parameter.

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15. Supplementary Notes

16. Abstract

A simulation study was conducted to investigate the piloting problems associated with failure of an engine on a generic light twin-engine airplane. A primary piloting problem for a light twin-engine airplane after an engine failure is maintaining precise control of the airplane in the presence of large steady control forces. To address this problem, a simulated automatic trim system which drives the trim tabs as an open-loop function of propeller slipstream measurements was developed. The simulated automatic trim system was found to greatly increase the controllability in asymmetric powered flight without having to resort to complex control laws or an irreversible control system. However, the trim-tab control rates needed to produce the dramatic increase in controllability may require special design consideration for automatic trim system failures. Limited measurements obtained in full-scale flight tests confirmed the fundamental validity of the proposed control law.

17. Key Words (Suggested by Authors(s)) Engine failure; Automatic controls; Light twin-engine airplanes; Piloted simulation	18. Distribution Statement Unclassified—Unlimited. Subject Category 02

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