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USE OF A LARGE JET TRANSPORT AS AN INFLIGHT DYNAMIC SIMULATOR

by

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SUMMARY

The supersonic transport configurations now being studied are considerably different from the existing subsonic jet transports and it is expected that the flight characteristics during the critical low-speed approach and landing will pose problems. In order to obtain information on these low-speed flight characteristics, the NASA-Langley Research Center contracted with The Boeing Company to modify the original Boeing 707 prototype (the model 367-80 airplane) for use ah an inflight simulator.

This paper will discuss the inflight simulation system that was developed for these tests. Included in the paper will be discussions of the unique use of spoilers and thrust reversers to simulate variations in lift and drag with angle of attack, the ability to vary the longitudinal characteristics to simulate the ground proximity, and the ground-based simulator and computer studies used to investigate problem areas and check the quality of simulation.

RESUME

Les configurations de l'avion de transport supersonique en cours d'étude étant sensiblement différentes de celles des avions à réaction subsoniques actuels, on s'attend à ce que les caractéristiques de vol au cours de la phase critique d'approche et d'atterrissage à faible vitesse présentent des problèmes. Pour obtenir des renseignements sur ces caractéristiques de vol à faible vitesse le centre de Recherche de la NASA à Langley a conclut un contrat avec la société Boeing relatif à la modification du prototype initial du Boeing 707 (modèle d'avion 367-80) en vue de son emploi en tant que simulateur en cours de vol.

Ce mémoire traitera du système de simulation en cours de vol élaboré pour ces essais. Il comportera aussi des discussions sur e'utilisation unique des spoilers et des inverseurs de poussée pour simuler les variations de la portance et de la traînée avec l'angle d'incidence, sur la possibilité de faire varier les caractéristiques longitudinales pour simuler la proximité du sol, ainsi que sur les études sur simulateur au sol et sur calculateur ayant pour but d'étudier les domaines donnant lieu à des problèmes et de contrôler la qualité de la simulation réalisée.

533.6.054:533.6.072:629.138.5

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William M. Eldridge and Harold L. Crane

1. INTRODUCTION

Several very large airplanes are currently being developed by US airframe manufacturers. Two such aircraft are the Boeing 747 and the supersonic transport (SST). They are not simply larger or faster variations of some existing subsonic or supersonic airplanes, but instead are the forerunners of a whole new generation of transport airplanes. For this reason, many of their flying characteristics will be wholly unlike present military or commercial models.

Some of these new airplanes will be nearly twice the gross weight of current transports - as much as 600,000 lb. Since weight increases create a marked change in aircraft handling characteristics, we can expect an immediate effect on the physical qualities of the new aircraft, particularly in terms of high wing loading, high inertia, and inertia distribution.

Increases in wing loading are directly traceable to the incorporation of newly developed high-lift flap systems, as well as to changes in aircraft low-altitude-cruise efficiency requirements. Wing loadings on the large jets will increase from a present level of 100 lb/ft^2 to 150 lb/ft^2.

The high inertia of these aircraft is of course the result of their high gross weight. A Boeing 747, for example, will have a pitch inertia 14 times greater than that of the 367-80 jet-transport prototype (see Figure 1). Differences of that kind, coupled with changes in inertia distribution, such as the large yaw/roll inertia ratio of the SST, will give the new airplanes stability and control response characteristics that are considerably different from those of present aircraft.

We expect that these new airplane designs may have control problems. The combination of high mass and inertia will make the airplane response to control sluggish. And to add to the problem, the changes in inertia distribution will cause motion cross-couplings that are likely to cause serious difficulties for the pilot.

Although the flying-quality requirements of the new airplanes are still uncertain, designers agree that they should be as good as, if not better than, present jet transports. The current problem is that these qualitative requirements have not yet been set down in quantitative form. Existing specifications for civil and military flying qualities are useful as a general guide, but a few of these have already become obsolete as a result of experience with present jet transports. Some requirements, such as longitudinal stability, have been too restrictive. Others, such as lateral control response, have not been restrictive enough. Indeed, what the designers need now is an accurate definition of large airplane control-response requirements in order to determine control system configurations and actuation power sizing.

Ground simulators, used extensively in the study of flying qualities, provide good solutions to the problems of cruise and instrument flight, but their use is often not valid in the evaluation of low-speed flight and landing characteristics. This is because a pilot, when landing an aircraft, must rely on a complex combination of visual, motion, and aircraft instrumentation cues while he is under the psychological pressure of performing the task well for his own and his passengers' safety.

2. DEVELOPMENT OF THE 367-80 INFLIGHT DYNAMIC SIMULATOR

Seeking to overcome the limitations of ground simulators, NASA's Langley Research Center, with Boeing, fitted the 367-80 prototype as an inflight dynamic simulator to study the low-speed flight and landing approach characteristics of large airplanes. The Boeing 367-80 airplane (see Figure 2) is the prototype of the C/KC-135 jet tanker-transport and of the company's current commercial aircraft series. Boeing has used the prototype extensively for development testing of high-lift flap systems*, many of which are now in use on the model 707, 720, and 727 jet transports.

2.1 History of Simulation Project

The history of this simulation project is shown in Figure 3. In 1963 a feasibility study had indicated that the 367-80 could be modified for simulation of both the variable-geometry and delta SST designs. Simulation equipment designed by Boeing was developed and installed in the test airplane in 1964. Initial check-out was made in 1965 during a company-funded C-5A simulation program. Five months, from May to October of 1965, were taken up with SST simulation tests conducted under contract to NASA. A similar program to study large subsonic transports was performed in November 1965 under contract to NASA's Ames Research Center.

2.2 Description of Boeing Model 367-80 Airplane

Throughout the simulation testing, the 367-80 was equipped with a blown boundary-layer control (BLC) flap system, an out-growth of the Boeing high-lift development program. This flap system (Fig.4) incorporates large, simple-hinged flaps that deflect to 85°. High-pressure engine bleed-air is blown over the upper surface through ejector nozzles. The wing has 727-type leading edge flaps and Kreuger flaps for maximum high-lift development.

A low-speed landing test program was conducted at NASA-Langley during the spring of 1964. During the program, which was described by Mr.Robert O.Shade at the 26th AGARD Flight Mechanics Panel meeting, the airplane demonstrated maximum lift coefficients of 3, stall speeds of 65 knots, and performed landing approaches as slow as 80 knots.

Several control problems were encountered during the low-speed tests. These included:

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* Autopilot improvement, and automatic landing systems.

Strong nonlinearities in the lateral control.

Unstable Dutch roll oscillation.

Strong aerodynamic roll/yaw cross-coupling.

Inadequate longitudinal-control power for flare in maximim ground effect.

Poor control resolution of the aerodynamic servo tabs at low speeds.

To overcome these problems, to allow tailoring of the control forces, and to simplify implementation of the simulation system, 727-type hydraulic-powered elevator and lateral-control systems (see Figure 5) were installed in the 367-80 in the fall of 1964.

Under a NASA-Langley test program during the same year, an advanced rudder-axis stability augmentation system was developed. That system consisted of a Dutch roll damper ($\delta R \sim \beta$) to give a Dutch roll damping ratio of 0.3, a roll decoupler ($\delta R \sim \dot{\phi}$) to eliminate adverse yaw resulting from roll rate, and a turn coordination programmer ($\delta R \sim \delta wH$ with phasing) to improve the turn-entry characteristics.

A system of aileron augmentation, incorporated in the design of the hydraulic-powered lateral-control system, consisted of a roll-rate damper ($\delta A \sim \dot{\phi}$), a yaw decoupler ($\delta A \sim \beta$) to reduce the large effective dihedral caused by wing sweep, and a spiral stability augmenter ($\delta A \sim \dot{\psi}$).

The low-speed rudder and aileron augmentation systems were evaluated in January 1965 in conjunction with NASA-Ames. Basic airplane lateral-directional characteristics were rated at 6 on the Cooper rating scale because of a divergent Dutch roll, adverse yaw, and strong excitation of lateral oscillations by the controls. With rudder augmentation, the pilot rating was improved to 3.5. Combined rudder and aileron augmentation was rated at 2.5 for low-speed landing approaches.

The 367-80 was equipped with a comprehensive system of instrumentation that measured airspeed, altitude, and temperature; all pilot-control inputs and control-surface positions; fuel loading and engine performance; angle of attack and sideslip; and computer output signals. Data were recorded by oscillographs and by magnetic tape. One tape system recorded 200 channels in sampled, digital form. The other tape system continuously recorded 40 channels. A self-developing oscillograph was used in flight to check out the airplane simulation quality.

2.3 Simulation Techniques

The 367-80 dynamic simulation system has five degrees of freedom, summarized in Figure 6. Rolling, yawing, and pitching moment equations are simulated by inputs to the lateral control, rudder, and elevator. The lift equation is simulated by inputs to the wing spoiler-type speed brakes, while the drag equation is simulated by inputs to the thrust modulators. There is no simulation of the side-force equation. However, both analytical and flight experience have shown that because the size, geometry, and airspeed of the 367-80 are close to those of the airplanes being simulated, stability characteristics and cockpit motion are within 90% of the correct values.

Inflight dynamic simulation uses the response-feedback technique (illustrated in Figure 7 for the pitch equation). The pilot's control inputs to the simulation computer are electrical signals. The computer duplicates the characteristics of the simulated - airplane control system, including the effects of control-time constants and rate limits. This signal is used to drive the 367-80 elevator. Resultant motions of the airplane are measured by the instrumentation, and signals are fed back through the computer circuits to the elevator to modify the natural stability characteristics of the -80 so that they match those of the airplane being simulated. In addition to the basic aerodynamic stability derivatives, the simulation equations include matching of control power and inertia. For simulation of delta-wing configurations the simulation equations include a transformation for the cross-product of inertia to give the correct dynamic stability modes and cockpit motion response. Complete simulation equations are given in the Appendix.

The 367-80 offers the evaluation pilot a very realistic flight experience with the simulated airplane. The accuracy of the airplane response to control and motions, and the correct indications of the cockpit instrument, give the pilot all his motion and visual cues. He can, with precision, evaluate a simulated aircraft configuration and his ability to control it. In addition, the aircraft's instrumentation makes a record of the way in which the pilot performs each task.

2.4 Airplane Mechanization

The simulation-evaluation pilot occupies the right-hand seat of the 367-80 cockpit. The right-hand control column, (Fig. 8) is identical with that of the left-hand seat except that it has been disconnected from the 367-80 control system. Electrical signal outputs are generated by the wheel and column. This unit is connected to artificial feel systems that provide the desired control forces. To allow the use of stick steering, the column is mechanized to generate either a deflection or force output signal. The lateral-feel system is a simple spring with a centering detent. The longitudinal-feel system has a fixed centering detent and variable-force gradient that incorporates a hydraulic spring. On the evaluation pilot's control wheel is a 707-type trim button that deflects the elevator with a signal from the computer. The normal 367-80 rudder control and feel spring are used and the control sensitivity and power are simulated by electrical inputs to the rudder through the yaw damper, which operates in series with the pilot's mechanical inputs. Evaluation pilot controls also include a throttle handle that operates the thrust modulators, through the computer, to simulate engine response.

The cockpit of the 367-80 is shown in Figure 9. The cockpit instrumentation is very similar to that of a 707 or 727. The instrumentation includes:

A Collins FD-108 flight director which provides heading, bank angle, pitch attitude, and slip information.

Flight director modes for VOR tracking, altitude hold, heading tracking, and ILS/ glide-slope capture and tracking.

An SR3 gyro compass, radio compass, ADF, and VOR.

Two airspeed systems, one the normal ship's system and the other connected to a pitot-static probe at the tip of the vertical tail.

Barometric and radar altimeter systems.

Indication of the angle of attack and sideslip angle, measured by the nose-boom vane.

A normal accelerometer and indication of wheel angle, elevator deflection, and stick force.

A bank of lights at the top of the panel monitors operation of the simulation system. The lights indicate saturation of any of the control surfaces or automatic disengagement of simulation. The simulation-throttle handle is to the right of the 367-80 throttles.

The airplane instrumentation and control systems interconnect with the simulation computer through the interface console (Fig. 10). Alternating-current signals from instruments, such as the gyro, are demodulated to d.c. signals for use by the computer. The interface contains power amplifiers for actuating the controls, rudder and aileron stability augmentation systems, and switching circuits to engage stability augmentation or simulation. In addition, the interface also provides signals for several instrumentation functions, such as the nose-boom vane indicators.

The simulation computer, (Fig. 11) is a Systron-Donner model SD-80 that has been modified and ruggedized for flight use. This computer has 84 transistorized amplifiers (100 V operation), 125 potentiometers, 15 nonlinear function generators, and 5 function switches.

The computer patchboard is removable, which allows a separate patchboard for each major simulation configuration. The computer mechanizes the feedback circuits that modify the 367-80 stability derivatives to those of the simulated configuration, and the circuits to simulate the control system response, control power and engine dynamic characteristics. The nonlinear function generators compensate for the aerodynamic nonlinearities of the 367-80, such as the speed-brake lift modulation, and simulate the nonlinearities, such as ground effect, of the airplane being evaluated. A unique feature of the simulation computer is that it includes an analog model of the 367-80 flight dynamics. Ground checkout of the simulation circuits is accomplished by connecting the control and feedback circuits to this model rather than to the interface. This very useful feature allows trouble shooting and configuration tailoring on the ground and has eliminated much unprofitable flight time.

The longitudinal, lateral, and directional controls and speed brakes are actuated by electric transfer valves on the hydraulic surface actuators (high-gain autopilot-type transfer valves that give fast control response and precise control resolution). The thrust modulators are actuated by an electric servo connected to the control cables. The wheel, column, and thrust modulators operate in parallel with the safety pilot's controls, which deflect to indicate the actual control surface position. The rudder and speed brakes, however, operate in series with the cockpit controls and their deflection is shown by cockpit instruments.

2.5 Special Features of the 367-80 Inflight Dynamic Simulator

The 367-80 is the first large jet airplane to be mechanized for inflight simulation. As a result of the 367-80's size, the pilot's cockpit environment is correct with the visibility, instruments, and noise typical of a present-day jet transport, and the cockpit motions and accelerations are representative of those of the large airplanes being simulated. Because the 367-80 can carry a large test crew, several pilots may participate on one flight and analysis engineers may also directly participate. The 367-80's large size also allows the use of off-the-shelf laboratory equipment, thus eliminating the need for miniaturization.

Lift characteristics are simulated by the 367-80's wing spoiler type speed brakes (see Figure 12). The airplane is trimmed with the speed brakes up, and the brakes are modulated up and down with angle of attack to change the lift-curve slope of the 367-80. Simulation of the lift curve of a variable-geometry SST is shown in Figure 13. The speed brakes also simulate lift interaction with power. The pitching moment and drag of the speed brakes are compensated in the simulation circuits.

Drag is simulated by the 367-80 thrust modulators (see Figure 12). The thrust modulators are thrust reversers that operate in the primary (hot flow) section of the engine. Hydraulic actuators connected to throttle-like handles in the cockpit drive the reverser clamshell doors. Since there is no fan section reversing, the thrust modulators produce a range of net thrust from full to zero. The airplane is trimmed with partial thrust modulation, and the thrust is modulated forward and back as a function of angle of attack and speed to simulate the desired drag and speed stability characteristics. Simulation of the drag of a variable-geometry SST is shown in Figure 14. The pitching moment and the altitude and temperature variations of the thrust modulators are compensated in the simulation circuits.

Ground effect in landing is approximately simulated by signals from a radar altimeter. (Fig.15). Three nonlinear function generators simulate the lift, drag, and pitching moment in ground effect by compensating the estimated 367-80 ground-effect characteristics and substituting those of the simulated airplane.

The 367-80 can operate in several alternative modes of flight: The safety pilot can fly the airplane using series rudder and aileron stability augmentation; the evaluation pilot's control can be connected to the basic 367-80 controls; and an autopilot mode is available.

2.6 Range of Simulation and Limitations

The 367-80 can operate in simulation over the full range of its aerodynamic performance and structural limitations, summarized in Figure 16. The BLC flap system will allow flight at landing approach speeds as low as 80 knots. Although structural placards presently limit simulation flight speeds to 160 knots, this can be increased to full subsonic cruise by minor structural and control system modifications. The structural limit on maneuvering is 1.6 g. The control deflection authority limits were chosen so that a hard-over signal from the computer would not upset the airplane or do structural damage before the safety pilot could recover control. These limits of control authority allow moderate to large amplitude maneuvers and can simulate the full control authority of high inertia airplanes.

The simulation is mechanized with linear, constant coefficient equations and is accurate over a speed range of ±10 knots from trim. The simulation accuracy is good at all 367-80 gross weights, with a maximum error of approximately 10% at high or low weight. Major configuration changes, such as flap or large trim speed changes, may not be made without disengaging the simulation and rescaling the computer.

2.7 Safety Provisions

The safety pilot monitors the operation of the controls and the maneuvers of the evaluation pilot, and takes command of the airplane if he observes a malfunction or senses an unsafe maneuver developing. The simulation can be disconnected electrically by either of the pilots. In addition, it will disconnect automatically when the interface senses a malfunction in the computer. If the electrical disconnect should fail to operate, the safety pilot can overpower the electrical control inputs with mechanical inputs. The control forces required to overpower the electrical system are:

Elevator	25 lb.
Lateral control	30 lb. + centering spring (= 45 lb. at 75° wheel).
Rudder	Centering spring (13 lb. at 10° δR).
Thrust modulators	60 lb. total.

2.8 Simulation Setup and Checkout

The response-feedback technique requires an accurate knowledge of the aerodynamics of the basic simulation airplane. Extensive wind-tunnel tests of a model of the 367-80 were performed to determine its longitudinal and lateral static derivatives. In addition, flight tests of the 367-80 were performed to determine:

Longitudinal static stability and lift-drag characteristics (by tests in which the airspeed was changed in increments of ±5 knots from trim).

Lateral-directional static stability, dihedral effect, and control characteristics (by performing cross-control sideslips).

Longitudinal short period and phugoid dynamic response (by performing step inputs to the column).

Longitudinal control sensitivity and power (by pitch reversals in which a control pulse input in one direction was followed by a step in the opposite direction).

Longitudinal maneuvering characteristics (by performing a wind-up turn and measuring the stick deflection, force per g, and angle-of-attack variation).

Roll response time constant and roll damping (by performing step wheel inputs and measuring the steady-state roll rate).

Lateral control sensitivity and power (by roll reversals similar to the pitch reversals).

Dutch roll mode (by measuring after pilot excitation).

Spiral stability (by establishing a steady banked turn and measuring the airplane divergence or convergence).

Airplane dynamic response to controls (by pulse inputs to each of the control surfaces and a step input to the thrust modulators). These pulses are programmed automatically by the computer and are trapezoidal, with a 1-second rise time, 2-second duration, and a 1-second decay time. The airplane response to these pulses is used in setting up the dynamic model of the 367-80 in the computer and for estimating the dynamic stability derivatives.

After the simulation patchboard is wired and the potentiometers set, the simulation circuits are connected to the 367-80 dynamic model for the initial simulation ground checkout. Control pulses of the wheel, column, and rudder, and a thrust step are then performed on the model and the computer responses are compared with the theoretical responses, calculated by a digital computer, of the airplane being simulated.

In flight, the airplane response to control pulses introduced by the computer is measured and compared with the theoretical response. If the response of the 367-80 is not correct, the simulation system gains are readjusted in flight until the response is correct. An elevator pulse for a simulated variable-geometry SST is shown in Figure 17. This simulation was very accurate. Simulation check pulses are performed for both high and low gross weights of the 367-80. When a configuration is flown that has been checked out previously, the check pulses are repeated to ensure that the simulation is operating correctly.

In the programs conducted to date, approximately 25% of the flight time has been required for the simulation checkout. This is the average for some easy configurations that checked out on the first try and some difficult ones that required one or more complete flights. In these test programs, each configuration was flown for approximately two flights. The repeatability was good, so that the configurations could be re-set at a later time.

After the pulse response checkout, the evaluation pilot performs a series of maneuvers to document the simulation configuration. Flight data from speed stability tests for a variable-geometry SST are shown in Figure 18. With the modulated speed brakes, the 367-80 lift simulation was very accurate. The flight data from a wind-up turn are shown in Figure 19, which shows that the 367-80 simulation of stick force per g was correct. In addition to these maneuvers, cross-control sideslips and control steps and reversals are performed and the dynamic stability modes are excited.

2.9 Simulation Testing

In the simulation programs to evaluate low-speed approach and landing characteristics, the evaluation pilots first performed a series of maneuvers at altitude to evaluate the stability and control response characteristics:

- Simulated descents and flares, to evaluate the maneuvering and speed control characteristics.
- Pitch attitude changes of 5^o and 10^o, to evaluate pitch response, stability, and damping.
- Roller-coaster maneuvers and wind-up turns, to evaluate maneuvering capabilities.
- Step wheel inputs and roll reversals, to evaluate roll response and lateral control power.
- Precision turns, large amplitude turns, and avoidance maneuvers, to evaluate turn characteristics.

Following the altitude maneuvers, visual and instrument approaches and landings were performed with each configuration. To make the control task more difficult, an offset was introduced to the ILS localizer signal that forced the pilot to fly back to the runway center line after breakout. If safety permitted, the evaluation pilot continued all approaches through landing. The landing simulation was realistic because of the ground-effect simulation. The landing simulation has been particularly valuable for evaluating airplane configurations with poor longitudinal control response, since the evaluation pilots have encountered pilot-induced oscillations and other problems that were not apparent during air maneuvers or landing approaches.

2.10 Simulation Programs Performed with the 367-80

The 367-80 inflight dynamic simulator was first used by Boeing to evaluate the C-5A. The Boeing C-5A design developed in the design competition was simulated to evaluate its flying qualities and to indicate any improvements that could be made. The C-5A lateral-directional stability augmentation system was implemented and evaluated. In addition, a research program was conducted to determine the lateral and longitudinal control response requirements.

An extensive SST simulation program was conducted at NASA-Langley. Typical variable-geometry and delta-wing SST configurations developed by NASA were evaluated. The basic unaugmented SST configurations were evaluated by three NASA pilots, and systems of longitudinal and lateral-directional stability augmentation were developed and evaluated. A number of degraded configurations, such as aft center of gravity and low Dutch roll damping, were also evaluated. At the conclusion of this program, the SST configurations were evaluated briefly by pilots from Boeing, Lockheed, NASA-Ames, and the FAA.

A simulation program to study the control requirements of large subsonic transports was performed in conjunction with NASA-Ames. This program evaluated the longitudinal and lateral control response requirements and the effects of the control system dynamics. This program was conducted in parallel with a ground-based simulator program, to get good correlation between ground simulation and flight.

3. CONCLUSIONS

The 367-80 inflight dynamic simulator is a versatile tool for evaluating new, large airplane designs. The 367-80 simulation is very accurate because it has five degrees of freedom. With its high-lift flaps, the 367-80 can simulate a wide range of airplane configurations through the STOL and conventional landing-approach speed range.

The simulation programs conducted to date have concentrated on airplane stability and control-response requirements for the landing task. Future programs will study emergency conditions, such as a partial control system or stability augmentation failures. When a specific design has been selected for the USA/SST, the 367-80 and other variable-stability airplanes will be used for development flight testing of the airplane aerodynamic configuration. The 367-80 can be profitably used for testing actual SST hardware, such as the autopilot, and will be useful for crew training prior to the first flight of the SST prototype.

The 367-80 also has great potential for research flight testing. With its removable patchboard, the computer can be mechanized for a wide variety of tests. Two possible areas of testing are in the fields of gust alleviation to reduce structural loads and improve riding qualities and the direct flight measurement of airplane stability derivatives.

APPENDIX

SIMULATION EQUATIONS

Airplane Equations of Motion
(Normalized)

Lift

$$(\dot{\theta} - \dot{\alpha}) - \frac{C_{L_\alpha}}{\frac{mV_0}{qS}} \Delta\alpha - \frac{\frac{2C_L}{V_0}}{\frac{mV_0}{qS}} \Delta V - \frac{C_{L_{\delta_{SB}}}}{\frac{mV_0}{qS}} \delta_{SB} = 0 .$$

Drag

$$\dot{V} + \frac{\frac{C_D}{V_0}}{\frac{m}{qS}} \Delta V + \frac{1/2 \left(C_{D_\alpha} - C_L\right)}{\frac{m}{2qS}} \Delta\alpha + \frac{\frac{C_L}{2}}{\frac{m}{qS}} \Delta\theta - \frac{\frac{\delta_{TH}}{2qS}}{\frac{m}{2qS}} = 0 .$$

Pitching Moment

$$\ddot{\theta} - \frac{C_{M_\alpha}}{\frac{I_y}{qS\bar{C}}} \Delta\alpha - \frac{C_{M_{\dot{\alpha}}}}{\frac{I_y}{qS\bar{C}}} \dot{\alpha} - \frac{C_{M_{\dot{\theta}}}}{\frac{I_y}{qS\bar{C}}} \dot{\theta} - \frac{C_{M_{\delta_e}}}{\frac{I_y}{qS\bar{C}}} \delta_e = 0 .$$

Rolling Moment

$$\ddot{\phi} - \frac{C_{l_\beta}}{\frac{I_x}{qSb}} \beta - \frac{C_{l_{\dot{\phi}}}}{\frac{I_x}{qSb}} \dot{\phi} - \frac{C_{l_{\dot{\psi}}}}{\frac{I_x}{qSb}} \dot{\psi} - \frac{C_{l_{\delta_A}}}{\frac{I_x}{qSb}} \delta_A - \frac{C_{l_{\delta_R}}}{\frac{I_x}{qSb}} \delta_R = 0 .$$

Yawing Moment

$$\ddot{\psi} - \frac{C_{n_\beta}}{\frac{I_z}{qSb}} \beta - \frac{C_{n_{\dot{\phi}}}}{\frac{I_z}{qSb}} \dot{\phi} - \frac{C_{n_{\dot{\psi}}}}{\frac{I_z}{qSb}} \dot{\psi} - \frac{C_{n_{\delta_A}}}{\frac{I_z}{qSb}} \delta A - \frac{C_{n_{\delta_R}}}{\frac{I_z}{qSb}} \delta_R = 0 .$$

Side Force

$$\dot{\beta} - \frac{Cy_{\phi}}{\frac{mV_0}{qS}}\Delta\phi - \frac{Cy_{\dot{\phi}}}{\frac{mV_0}{qS}}\dot{\phi} - \frac{Cy_{\beta}}{\frac{mV_0}{qS}}\beta - \frac{Cy_{\dot{\psi}}}{\frac{mV_0}{qS}}\dot{\psi} - \frac{Cy_{\delta_R}}{\frac{mV_0}{qS}}\delta_R = 0 .$$

I_x, I_z = Stability axis inertias.

Dynamic Simulation Equations

Elevator

$$\delta_e = \frac{\delta_e}{\delta\alpha}\Delta\alpha + \frac{\delta_e}{\dot{\alpha}}\dot{\alpha} + \frac{\delta_e}{\dot{\theta}}\dot{\theta} .$$

Speed Brakes

$$\delta_{SB} = \frac{\delta_{SB}}{\delta\alpha}\Delta\alpha + \frac{\delta_{SB}}{\delta V}\Delta V .$$

Thrust Modulators

$$\delta_{TH} = \frac{\delta_{TH}}{\delta\alpha}\Delta\alpha + \frac{\delta_{TH}}{\delta\theta}\Delta\theta + \frac{\delta_{TH}}{\delta V}\Delta V .$$

Aileron

$$\delta_A = \frac{\delta_A}{\beta}\beta + \frac{\delta_A}{\dot{\phi}}\dot{\phi} + \frac{\delta_A}{\dot{\psi}}\dot{\psi} .$$

Rudder

$$\delta_R = \frac{\delta_R}{\beta}\beta + \frac{\delta_R}{\dot{\phi}}\dot{\phi} + \frac{\delta_R}{\dot{\psi}}\dot{\psi} .$$

Dynamic Simulation System Gains

Let

$$A = \frac{m}{qS}, \quad B = \frac{I_y}{qS\bar{c}}, \quad C = \frac{I_x}{qSb}, \quad D = \frac{I_z}{qSb}.$$

$$\frac{\delta e}{\alpha} = \frac{\left.\frac{C_{m_\alpha}}{B}\right]_{SST} - \left.\frac{C_{m_\alpha}}{B}\right]_{-80}}{\left.\frac{C_{m_{\delta_e}}}{B}\right]_{-80}}, \qquad \frac{\delta e}{\dot{\alpha}} = \frac{\left.\frac{C_{m_{\dot{\alpha}}}}{B}\right]_{SST} - \left.\frac{C_{m_{\dot{\alpha}}}}{B}\right]_{-80}}{\left.\frac{C_{m_{\delta_e}}}{B}\right]_{-80}}$$

$$\frac{\delta e}{\theta} = \frac{\left.\frac{C_{m_{\dot{\theta}}}}{B}\right]_{SST} - \left.\frac{C_{m_{\dot{\theta}}}}{B}\right]_{-80}}{\left.\frac{C_{m_{\delta_e}}}{B}\right]_{-80}}, \qquad \frac{\delta_{SB}}{\delta\alpha} = \frac{\left.\frac{C_{L\alpha}}{AV_0}\right]_{SST} - \left.\frac{C_{L_\alpha}}{AV_0}\right]_{-80}}{\left.\frac{C_{L_{\delta_{SB}}}}{AV_0}\right]_{-80}}$$

$$\frac{\delta_{SB}}{V} = \frac{\left.\frac{2C_L/V_0}{AV_0}\right]_{SST} - \left.\frac{2C_L/V_0}{AV_0}\right]_{-80}}{\left.\frac{C_{L_{\delta_{SB}}}}{AV_0}\right]_{-80}}, \qquad \frac{\delta_A}{\beta} = \frac{\left.\frac{C_{l_\beta}}{C}\right]_{SST} - \left.\frac{C_{l_\beta}}{C}\right]_{-80}}{\left.\frac{C_{L_{\delta_A}}}{C}\right]_{-80}}$$

$$\frac{\delta_A}{\dot{\phi}} = \frac{\left.\frac{C_{l_{\dot{\phi}}}}{C}\right]_{SST} - \left.\frac{C_{l_{\dot{\phi}}}}{C}\right]_{-80}}{\left.\frac{C_{l_{\delta_A}}}{C}\right]_{-80}}, \qquad \frac{\delta_A}{\dot{\psi}} = \frac{\left.\frac{C_{l_{\dot{\psi}}}}{C}\right]_{SST} - \left.\frac{C_{l_{\dot{\psi}}}}{C}\right]_{-80}}{\left.\frac{C_{l_{\delta_A}}}{C}\right]_{-80}}$$

$$\frac{\delta_{TH}}{\delta\alpha} = -\left\{\left.\frac{(C_{D_\alpha} - C_L)}{A}\right]_{SST} - \left.\frac{(C_{D_\alpha} - C_L)}{A}\right]_{-80}\right\} m\Big]_{-80}$$

$$\frac{\delta_{TH}}{\delta V} = -\left\{\left.\frac{2\frac{C_D}{V_0}}{A}\right]_{SST} - \left.\frac{2\frac{C_D}{V_0}}{A}\right]_{-80}\right\} m\Big]_{-80}$$

$$\frac{\delta_R}{\beta} = \frac{\left.\frac{C_{n_\beta}}{D}\right]_{SST} - \left.\frac{C_{n_\beta}}{D}\right]_{-80}}{\left.\frac{C_{n_{\delta_R}}}{D}\right]_{-80}}$$

$$\frac{\delta_R}{\phi} = \frac{\left.\frac{C_{n\dot{\phi}}}{D}\right]_{SST} - \left.\frac{C_{n\dot{\phi}}}{D}\right]_{-80}}{\left.\frac{C_{n\delta_R}}{D}\right]_{-80}}$$

$$\frac{\delta_R}{\psi} = \frac{\left.\frac{C_{n\dot{\psi}}}{D}\right]_{SST} - \left.\frac{C_{n\dot{\psi}}}{D}\right]_{-80}}{\left.\frac{C_{n\delta_R}}{D}\right]_{-80}} \quad .$$

Cross-Coupling Compensation

$$\frac{\delta_{TH}}{\delta_{SB}} = C_{D_{\delta_{SB}}} qS, \qquad \left.\frac{\delta_R}{\delta_A}\right) = -\frac{C_{n_{\delta_A}}}{C_{n_{\delta_R}}}$$

$$\frac{\delta_e}{\delta_{SB}} = -\frac{C_{m_{\delta_{SB}}}}{C_{m_{\delta_e}}}, \qquad \left.\frac{\delta_A}{\delta_R}\right) = -\frac{C_{l_{\delta_R}}}{C_{l_{\delta_A}}} \quad .$$

Control Authority Simulation

$$\frac{\delta_{R_{-80}}}{\delta_{R_{SST}}} = \frac{\left.\frac{C_{n_{\delta_R}} \delta_{R_{MAX}}}{D}\right|_{SST}}{\left.\frac{C_{n_{\delta_R}} \delta_{R_{MAX}}}{D}\right|_{-80}}, \qquad \frac{\delta_{A_{-80}}}{\delta_{A_{SST}}} = \frac{\left.\frac{C_{l_{\delta_A}} \delta_{A_{MAX}}}{C}\right|_{SST}}{\left.\frac{C_{l_{\delta_A}} \delta_{A_{MAX}}}{C}\right|_{-80}}$$

$$\frac{\delta_{e_{-80}}}{\delta_{e_{SST}}} = \frac{\left.\frac{C_{m_{\delta_e}} \delta_{e_{MAX}}}{B}\right|_{SST}}{\left.\frac{C_{m_{\delta_e}} \delta_{e_{MAX}}}{B}\right|_{-80}} \quad .$$

Inertia Cross-Product Transformation

For the simulation of airplanes, such as the delta-wing SST, with a high cross-product of inertia, the following changes are made to the basic simulation equations:

(i) Use stability axis inertias, I_x, I_Z, J_{xz}.

(ii) In the roll and yaw equations, replace the rolling and yawing moments of inertia by

$$I_x \longrightarrow I_x - \frac{J_{xz}^2}{I_z}, \qquad I_z \longrightarrow I_z - \frac{J_{xz}^2}{I_x} \ .$$

(iii) Replace the aerodynamic stability and control coefficients by

$$C_{l_\beta} \longrightarrow C_{l_\beta} + \frac{J_{xz}}{I_z} C_{n_\beta}$$

$$C_{l_{\dot\phi}} \longrightarrow C_{l_{\dot\phi}} + \frac{J_{xz}}{I_z} C_{n_{\dot\phi}}$$

$$C_{l_{\dot\psi}} \longrightarrow C_{l_{\dot\psi}} + \frac{J_{xz}}{I_z} C_{n_{\dot\psi}}$$

$$C_{l_{\delta_{wH}}} \longrightarrow C_{l_{\delta_{wH}}} + \frac{J_{xz}}{I_z} C_{n_{\delta_{wH}}}$$

$$C_{l_{\delta_R}} \longrightarrow C_{l_{\delta_R}} + \frac{J_{xz}}{I_z} C_{n_{\delta_R}}$$

$$C_{n_\beta} \longrightarrow C_{n_\beta} + \frac{J_{xz}}{I_x} C_{l_\beta}$$

$$C_{n_{\dot\phi}} \longrightarrow C_{n_{\dot\phi}} + \frac{J_{xz}}{I_x} C_{l_{\dot\phi}}$$

$$C_{n_{\dot\psi}} \longrightarrow C_{n_{\dot\psi}} + \frac{J_{xz}}{I_x} C_{l_{\dot\psi}} \quad ^*$$

$$C_{w_{\delta_{wH}}} \longrightarrow C_{n_{\delta_{wH}}} + \frac{J_{xz}}{I_x} C_{l_{\delta_{wH}}}$$

$$C_{n_{\delta_R}} \longrightarrow C_{n_{\delta_R}} + \frac{J_{xz}}{I_x} C_{l_{\delta_R}} \ .$$

* If there is a large difference between α_{-80} and α_{sim} this gain should be reduced to avoid an unrealistic adverse yaw in the cockpit caused by the -80 body axis being below the simulated roll axis.

(iv) Use $\dot{\phi}_s$ and $\dot{\psi}_s$ for the simulation feedback rather than $\dot{\phi}_B$ and $\dot{\psi}_B$ generated by the instrumentation:

$$\dot{\phi}_s = \dot{\phi}_B \cos\alpha + \dot{\psi}_B \sin\alpha$$

$$\dot{\psi}_s = -\dot{\phi}_B \sin\alpha + \dot{\psi}_B \cos\alpha \quad .$$

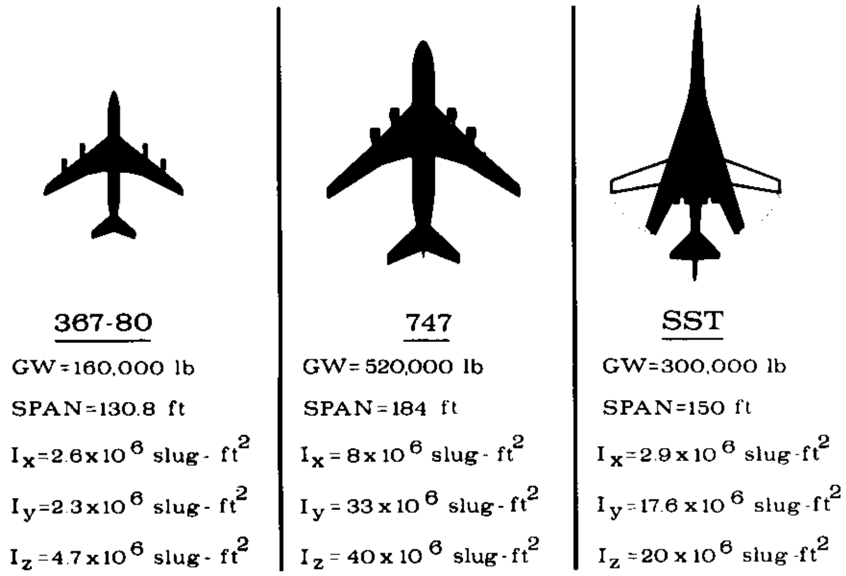


Fig. 1 Airplane comparison

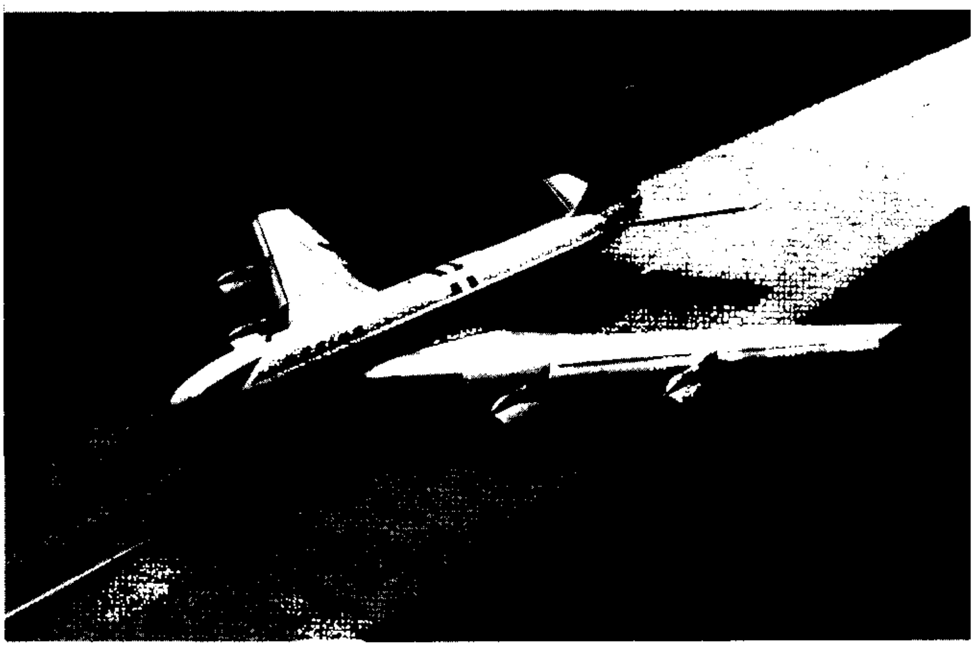


Fig. 2 Boeing 367-80

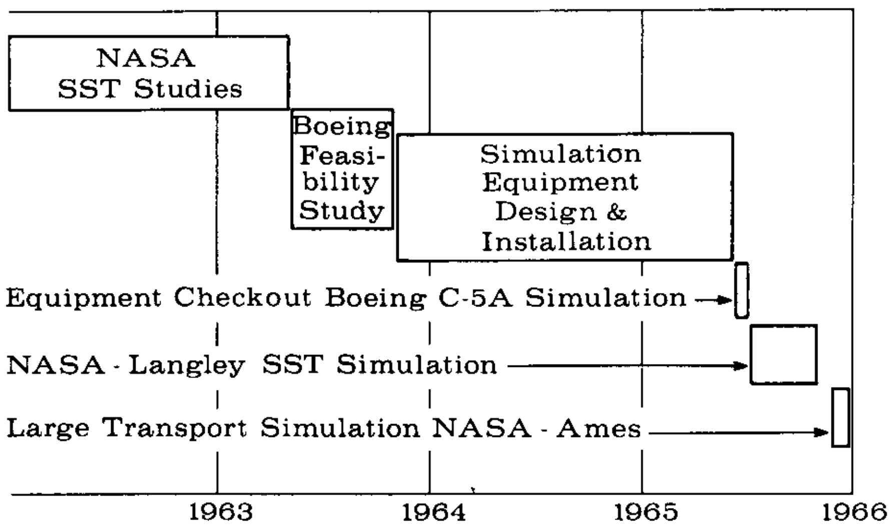


Fig. 3 Simulation development

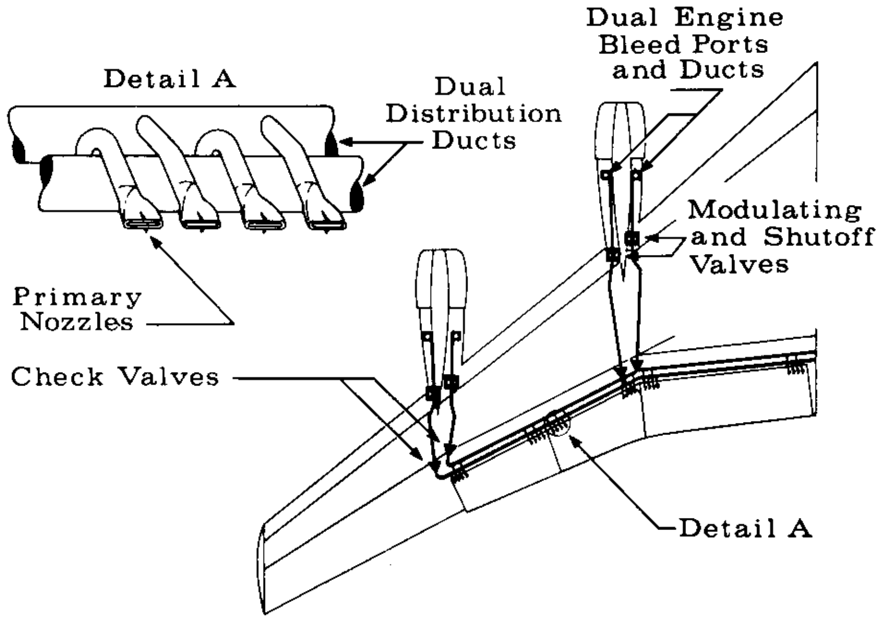


Fig. 4 Boundary-layer control flap system

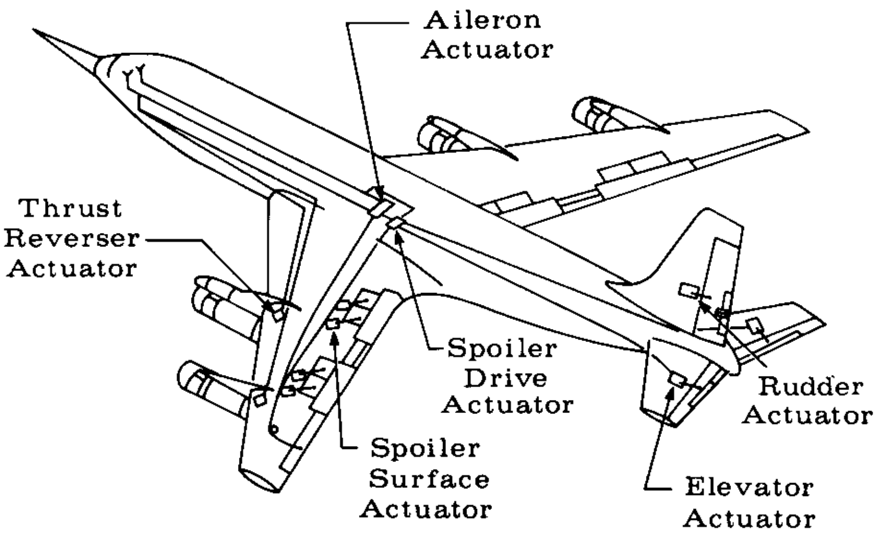


Fig. 5 Powered control system

Pitching Moment	Elevator Control
Rolling Moment	Lateral Control
Yawing Moment	Rudder Control
Lift	Modulated Speed Brakes
Drag	Modulated Thrust Reversers
Side Force	No Simulation

Fig. 6 Simulation techniques

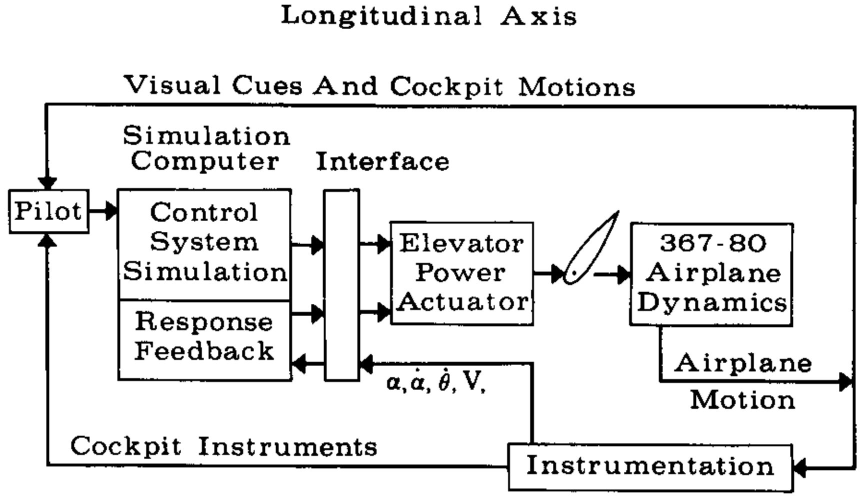


Fig.7 367-80 simulation system

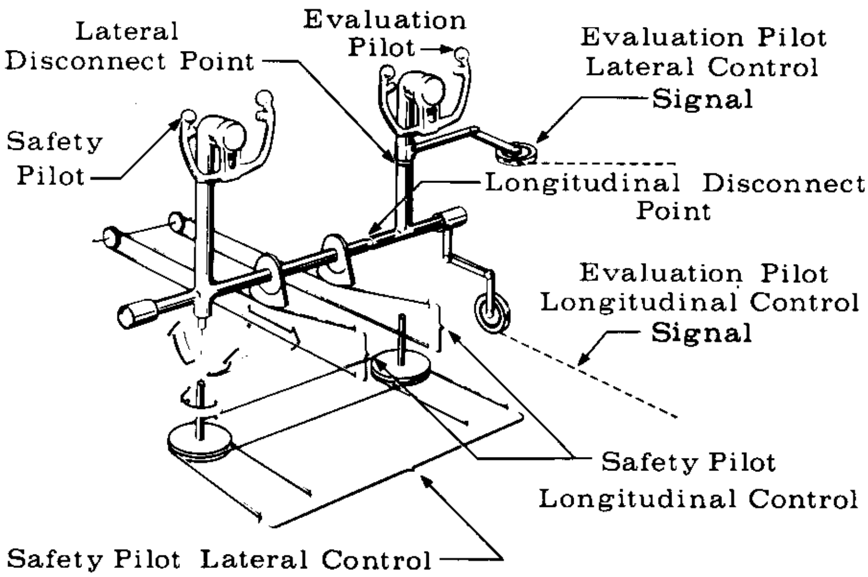


Fig.8 Control separation

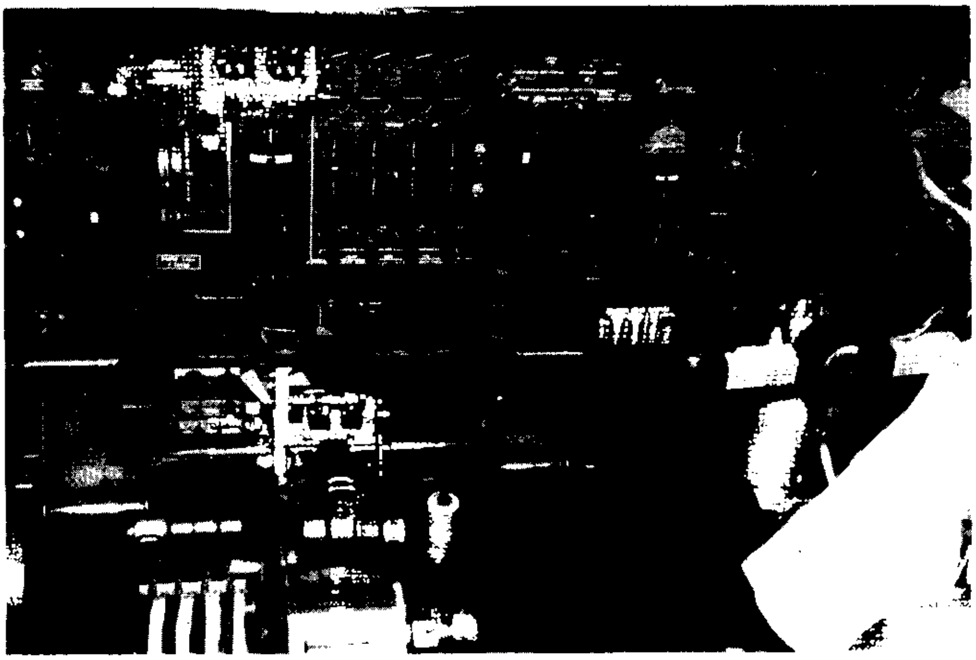


Fig. 9　Boeing 367-80 cockpit

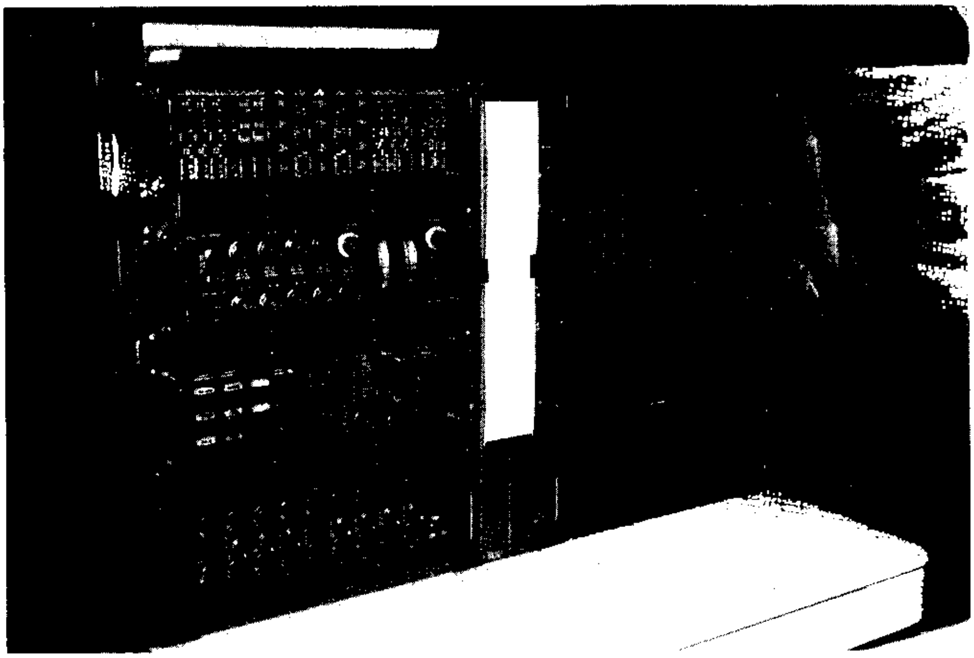


Fig. 10　Interface console

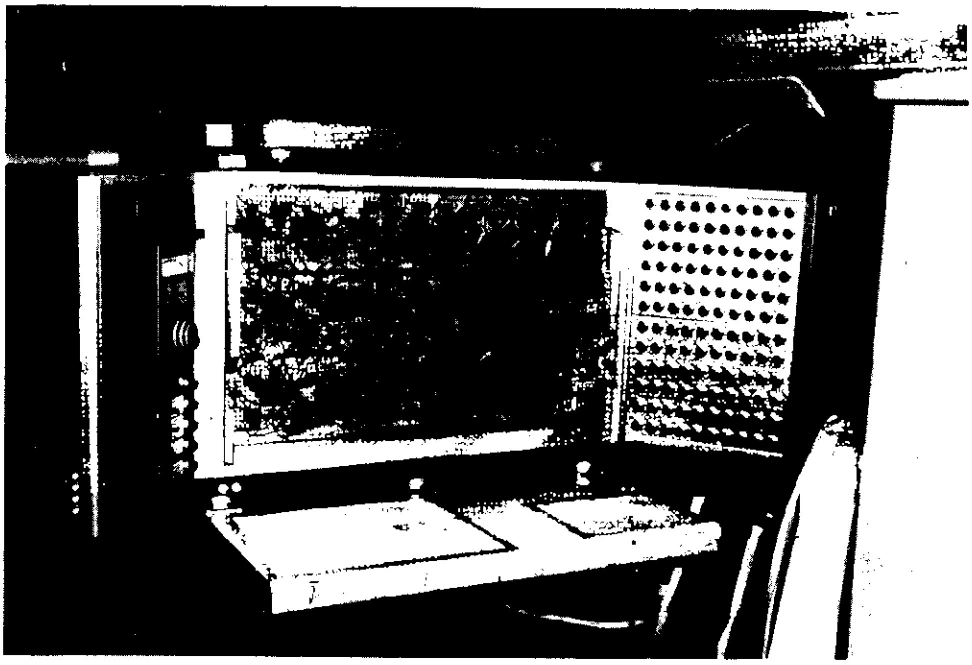


Fig. 11 Simulation computer

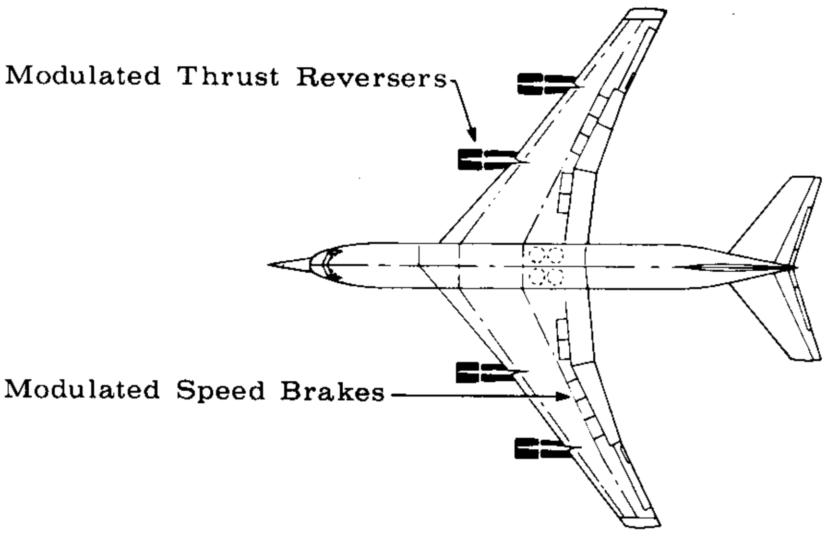


Fig. 12 Lift-drag simulation

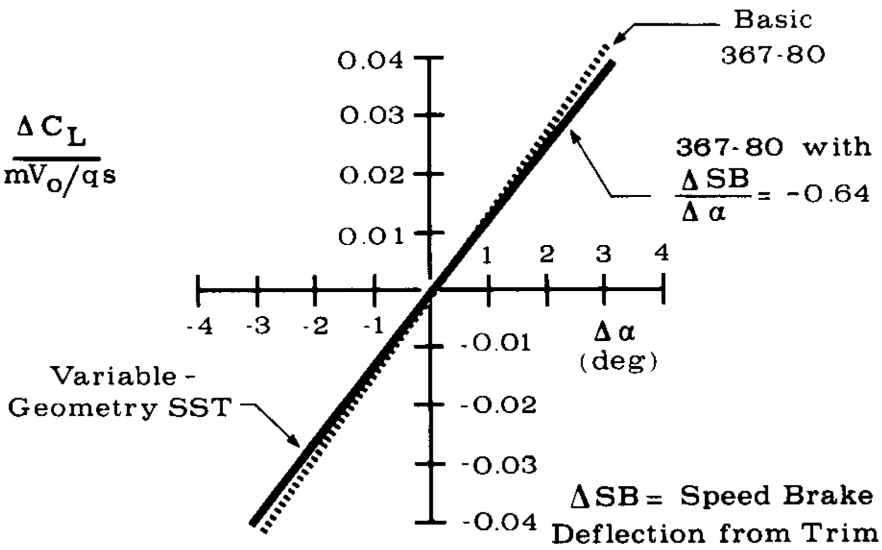


Fig. 13 Lift simulation

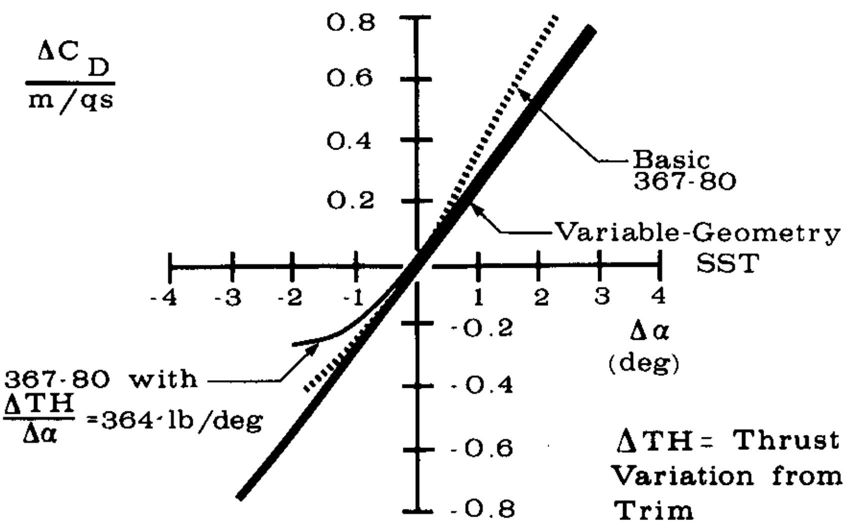


Fig. 14 Drag simulation

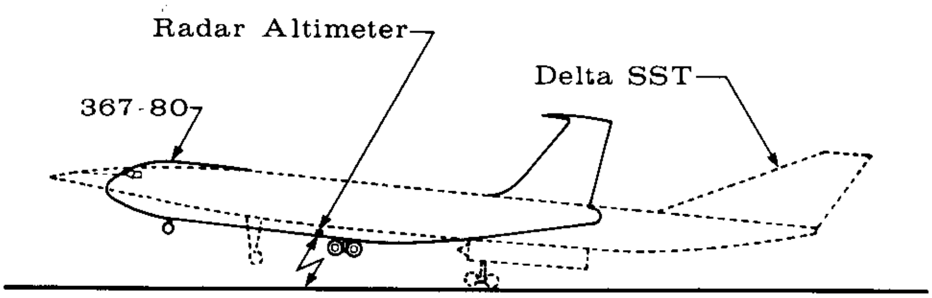


Fig. 15 Radar altimeter

Airspeed 80 to 160 KN (With Modifications, M0.8)

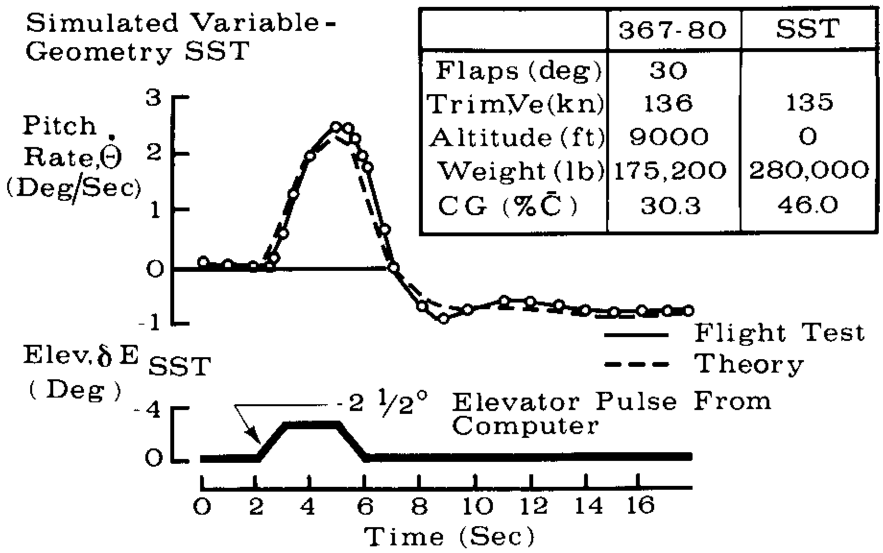
Maneuvering 1.6G

Control Surface Deflections

	Rudder	10°	(40%)
	Lateral Control	60° Wheel	(80%)
	Elevator	10°	(40%)

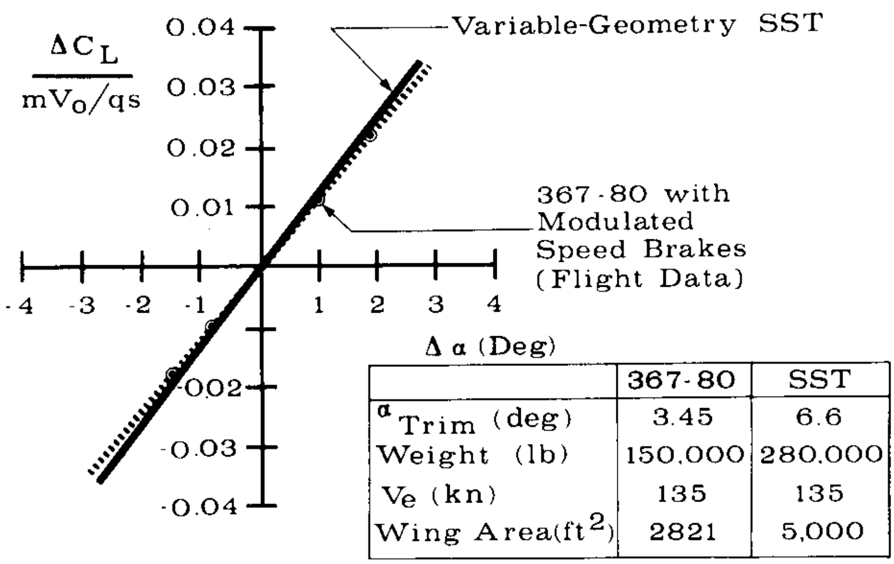
Linear Simulation ±10 KN From Trim

Fig. 16 Range of simulation



	367-80	SST
Flaps (deg)	30	
Trim Ve(kn)	136	135
Altitude (ft)	9000	0
Weight (lb)	175,200	280,000
CG (%C̄)	30.3	46.0

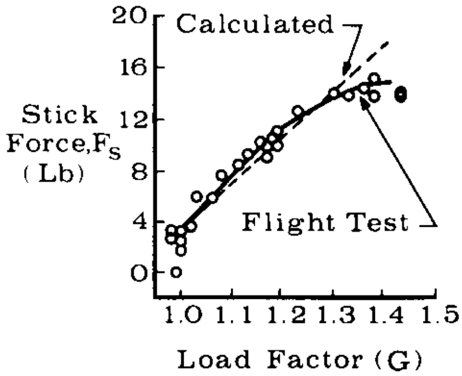
Fig. 17 Pulse response in flight



	367-80	SST
α_{Trim} (deg)	3.45	6.6
Weight (lb)	150,000	280,000
Ve (kn)	135	135
Wing Area (ft^2)	2821	5,000

Fig. 18 Lift documentation

Simulated Variable-Geometry SST



Data From Wind-Up Turn

	367-80	SST
Flaps(deg)	30	
Altitude(ft)	5600	0
TrimVe(kn)	134	135
Weight(lb)	150,000	280,000
CG (%$\bar{C}$)	29.3	46

Fig. 19 Maneuvering documentation. Wind-up turn

The following page(s) provide higher quality versions of graphics contained in the preceding article or section.

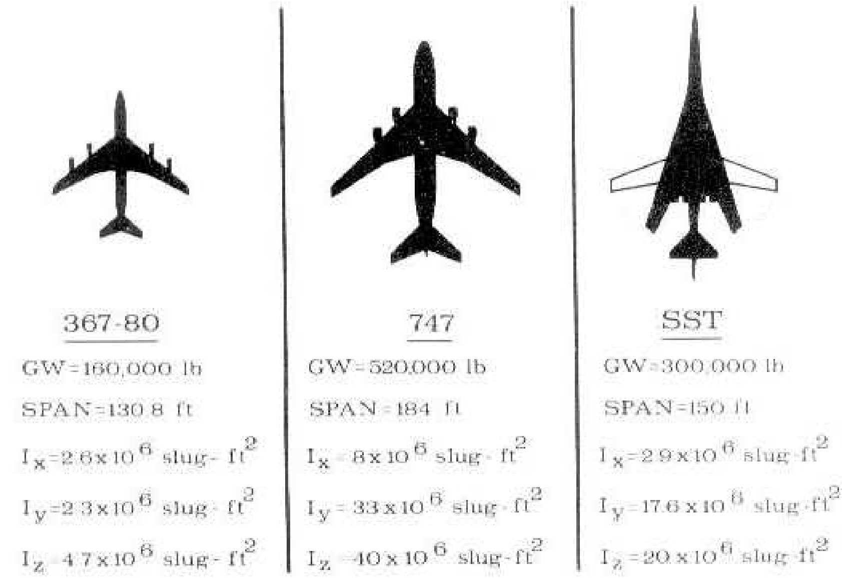


Fig. 1 Airplane comparison

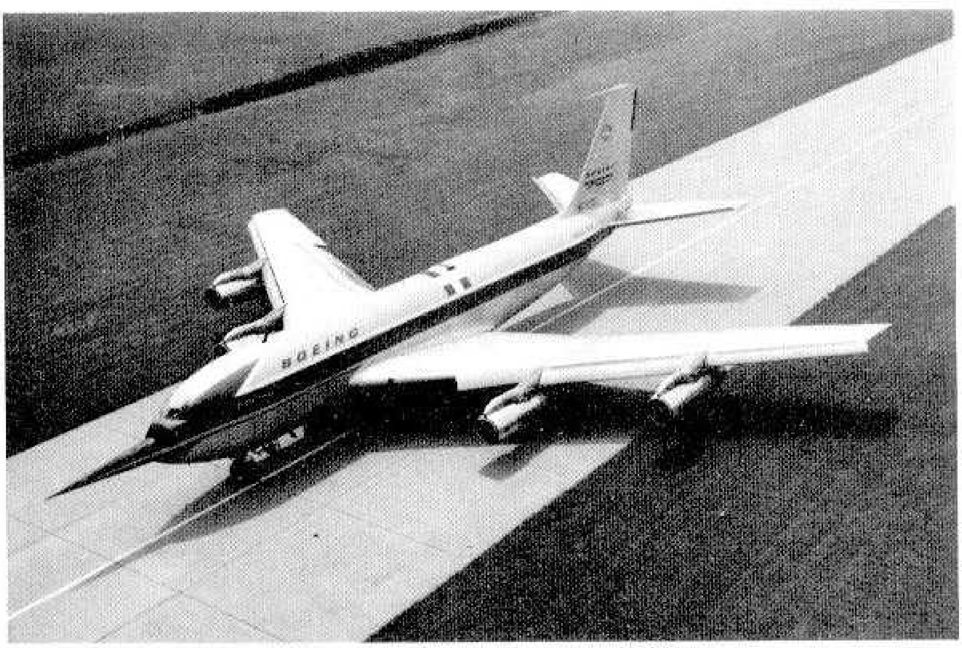


Fig. 2 Boeing 367-80

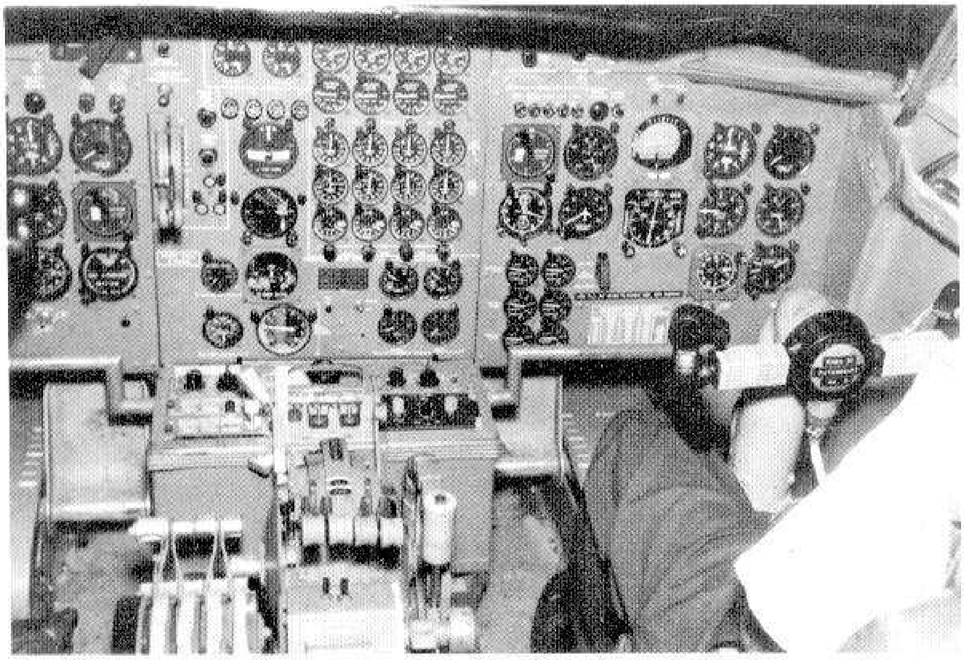


Fig. 9　Boeing 367-80 cockpit

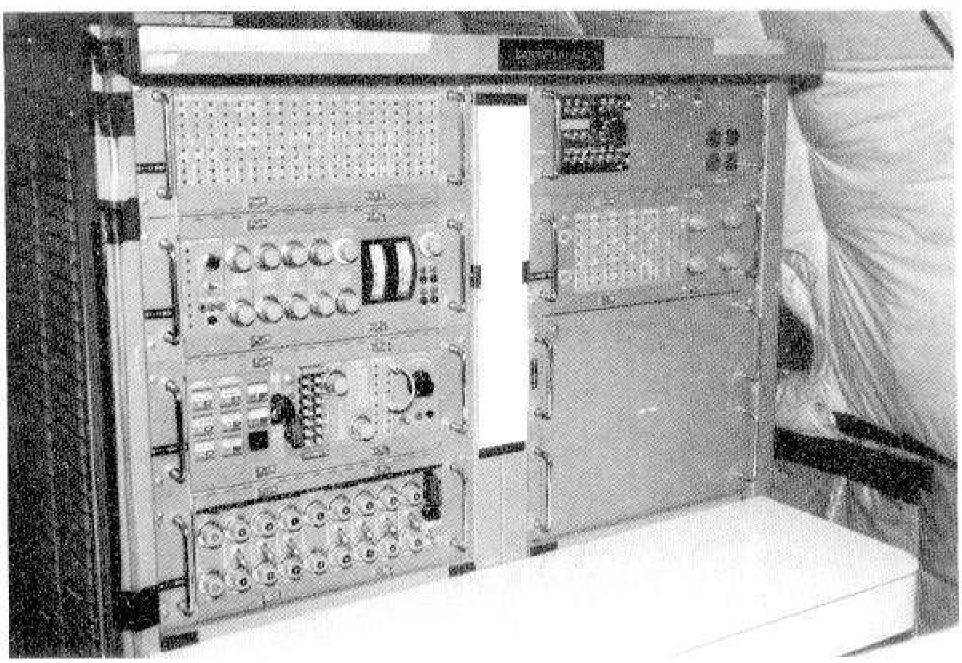


Fig. 10　Interface console

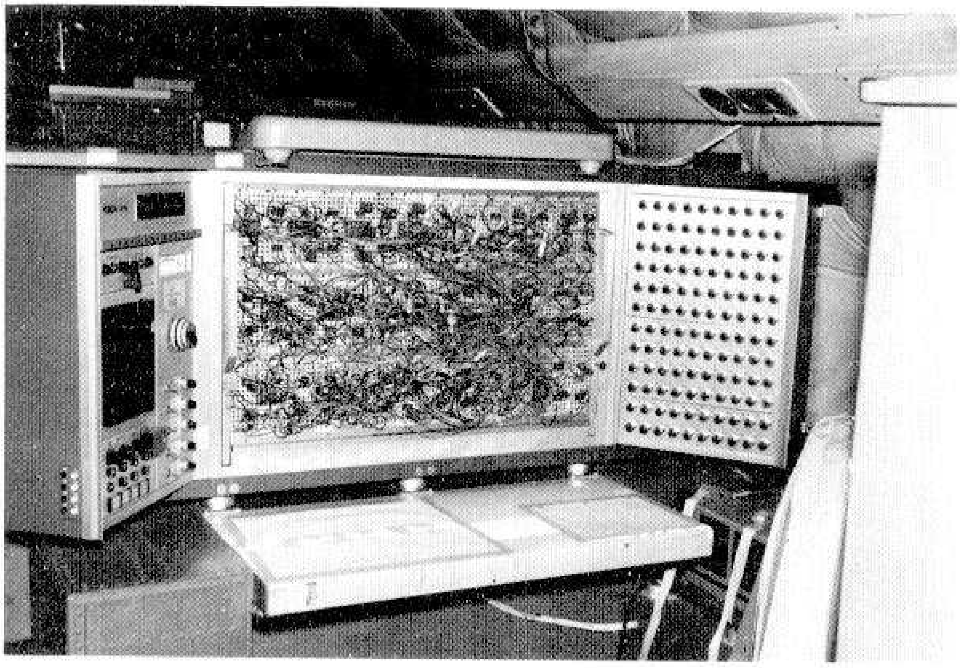


Fig.11　Simulation computer

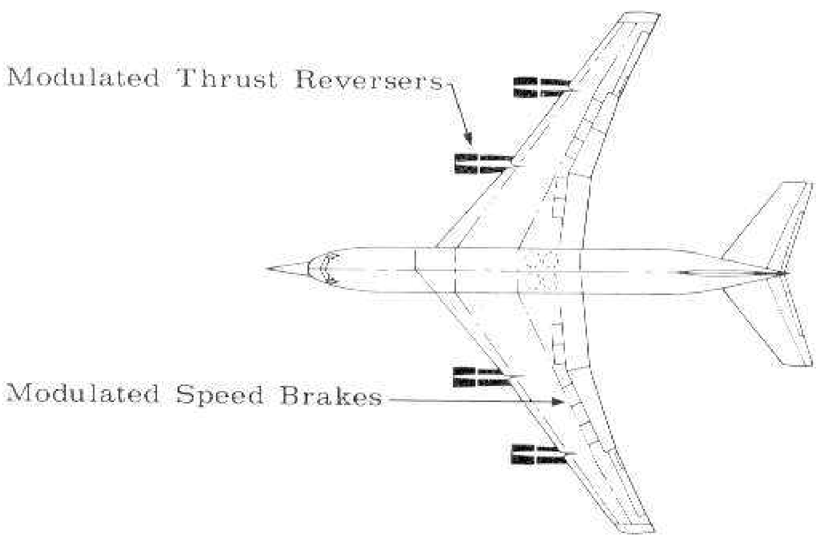


Fig.12　Lift-drag simulation