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James A. Albers

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16. Abstract

The YF-12 research program was initiated to establish a technology base for the design of an efficient propulsion system for supersonic cruise aircraft. The major technology areas under investigation in this program are inlet design analysis, propulsion system steady-state performance, propulsion system dynamic performance, inlet and engine control systems, and airframe/propulsion system interactions.

This report discusses the objectives, technical approach, and status of the YF-12 propulsion program. It discusses the results obtained to date by the NASA Ames, Lewis, and Dryden research centers. The expected technical results and proposed future programs are also given.

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James A. Albers
Dryden Flight Research Center

INTRODUCTION

Supersonic transport aircraft require propulsion systems that operate efficiently through a wide range of altitudes, and at speeds from subsonic to high supersonic cruise. To avoid penalties in engine size, weight, and fuel consumption, the inlet system must be designed to supply air at the maximum pressure with minimal drag and interference. The inlet system must also be able to match the airflow requirements of the engine over a wide range of flight conditions. To optimize an inlet for a given aircraft mission requires extensive tradeoffs between performance at design and at off-design conditions.

A first step in the optimization of the propulsion system is an analytical study of the various inlet geometries that match the engine requirements. This is followed by wind tunnel testing of scaled models prior to flight testing. In general, conditions in the wind tunnel do not exactly duplicate flight conditions. With scaled models, the Reynolds numbers and the local flow field do not always correspond to those in flight. In addition, the geometry and the instrumentation location and accuracy of wind tunnel models are difficult to match to those of the flight hardware. Since the flight hardware and its expected performance are determined from scaled wind tunnel models, scaling techniques that allow the extrapolation of subscale inlet data to full-scale flight are necessary.

Many of the current propulsion system problems for supersonic cruise aircraft involve inlet-engine compatibility. Insufficient propulsion system stability margin caused by pressure distortion has been and continues to be a significant problem in aircraft development. It is presently not clear how dynamic data from model tests can be used to predict the stability margin of the propulsion system in flight.

Another area of major concern to the propulsion system designer is the prevention of the inlet unstarts, which result when the terminal shock moves out in front of the cowl lip. Unstarts can occur when either internal disturbance or external disturbance occurs in flight. New propulsion control concepts are needed to position the terminal shock in the inlet duct. At present, mixed-compression inlets have variable geometry features that are programed by a variety of engine, inlet, and airframe variables. For example, in the YF-12 inlet, variable bypass doors and a spike or ramp move as functions of Mach number, angle of attack, normal acceleration, and angle of sideslip. New stability bleed systems and shock position sensors are required to improve the response of the present control system.

Experience to date with supersonic cruise aircraft has indicated strong interactions between the propulsion system and the flight control system. These effects have been traced to the porting of bleed and bypass flows overboard around the nacelle. This can result in separated flow on the external nacelle and in the base and boattail region surrounding the engine exhaust. Thus, the nacelle flow interactions of supersonic cruise aircraft require further investigation. An integrated overall aircraft control system is needed to minimize the undesirable interactions of the inlet, engine, and airframe control systems.

To establish a technology base for the design of an efficient propulsion system for supersonic cruise aircraft, a propulsion research program using the YF-12 airplane was initiated in 1969. This report discusses the objectives, technical approach, and status of this propulsion program. It discusses the results obtained to date by Ames, Lewis, and Dryden research centers. The expected technical results and proposed future programs are also discussed.

OBJECTIVES

The primary objective of the YF-12 propulsion program is to establish a technology base for an efficient inlet system (fig. 1) for supersonic cruise aircraft. The major technology areas under investigation in this program are inlet design analysis and prediction techniques, propulsion system steady-state performance, propulsion system dynamic performance and inlet-engine compatibility, inlet and engine control systems, and airframe/propulsion system interactions.

The objectives of the program are as follows: to develop analysis techniques in order to optimize inlet geometries and bleed systems for mixed-compression inlets; to evaluate the effects of Reynolds number, scaling, flow field, and other wind tunnel and flight differences on propulsion system performance; to evaluate the overall steady-state inlet performance and to determine the operation range of the inlet for various geometries and flow conditions; to develop scaling techniques that permit the extrapolation of subscale inlet dynamics to full-scale flight; to evaluate the effects of high frequency flow fluctuations, or transients, on the stability of the propulsion system; to evaluate new control concepts and stabilization techniques for a mixed-compression propulsion system; to measure and evaluate the effects of atmospherically induced turbulence on the dynamics of mixed-compression inlets; to develop dynamic pressure sensors and other instrumentation for propulsion system testing; to investigate the causes of airframe/propulsion system interactions; and to utilize the YF-12 airplane as a test bed to investigate new propulsion system concepts, such as turbofan ramjet and variable cycle engine concepts.

TECHNICAL APPROACH

With the use of specially developed high temperature instrumentation, steady-state and dynamic inlet performance was measured. Comparisons are being made between flight data and data from 1/3-scale and full-scale wind tunnel test of the inlet. Methods of extrapolation from wind tunnel to full scale are being developed. A comparison of inlet configurations and test facilities is shown in figure 2. A schematic of the YF-12 duct pressure instrumentation is given in figure 3. Wind tunnel and flight evaluations of advance propulsion control concepts, including inlet shock stabilization, are being made. An example of new control concepts presently being studied is Lewis' stability bleed system, which is shown in figure 4. An integrated propulsion/flight control system (YF-12 cooperative control system) is being developed and is to be evaluated for its usefulness in flight. A conceptual schematic of this integrated control system is shown in figure 5. The interactions between the airplane and the propulsion system could be studied by comparing the flight data with 1/12-scale airplane model data. Some results of a tuft study which show the local flow around a nacelle in flight are shown in figure 6. These experimental results are to be used to refine the analytical models and propulsion simulations. The YF-12 aircraft is to be used as a test bed for the evaluation of future propulsion concepts.

PROGRAM STATUS

Inlet Design Analysis

At the time that the YF-12 propulsion program was initiated, limited design analysis was done in direct support of the program. However, through research programs at Ames and Lewis, a technology base for supersonic inlet design computations has been developed. The inviscid flow analysis of supersonic inlet flow fields (refs. 1 to 3) utilizes the method of characteristics. A boundary layer study of an inlet that uses a bleed system designed for Mach numbers of 2.5 and below is given in reference 4. A bleed study on flat plates is given in reference 5. A viscous flow analysis that is presently being developed to design inlet diffusers is discussed in reference 6. Design analysis for mixed-compression inlets for Mach numbers greater than 2.5 has been done at Ames and sponsored by Ames. Some recent contract work that has direct application to design bleed systems for supersonic inlets for Mach numbers greater than 2.5 is reported in reference 7. An evaluation of this analytical technique is given in reference 8. These analysis techniques could be used to design new inlets for supersonic cruise aircraft. A promising high Mach number inlet has been tested and reported in reference 9. Recent analysis indicates that this inlet can be further developed by using the analytical bleed design methods used in references 7 and 8. In addition, the capability now exists to evaluate inlet flow fields at moderate angles of attack (ref. 10).

Propulsion System Steady-State Performance

1/3-scale test results. - A 1/3-scale model of the YF-12 inlet (fig. 7) was tested at Ames in the Unitary Plan Facilities at Mach numbers from 0.9 to greater than 3, and at Reynolds numbers (based on inlet diameter) between 5×10^6 and 7×10^6. The aircraft inlet internal geometry was completely simulated from the centerbody tip to the engine face station, including the variable forward and aft bypass doors and the centerbody and cowl bleed systems. The tests involved the investigation and correlation of the steady-state inlet parameters between the airplane and the model and the investigation and assessment of the effects of scale on the frequency and amplitude phenomena of inlet dynamic turbulence. Hence, a large amount of steady-state and dynamic instrumentation was incorporated in the model. The basic data (including mass flow rates, pressure recovery, distortion parameters, boundary layer surveys, and dynamic data) have been obtained, and the steady-state results are completely documented in references 11 to 13. The dynamic information has not been reduced or analyzed except for a limited statistical analysis reported in reference 12; all dynamic information is recorded on magnetic tapes that are stored at Ames. Analysis of these data and correlations with flight data are discussed in a subsequent section of this document.

Full-scale test results. - An extensive steady-state investigation has been completed in Lewis' 10-Foot × 10-Foot Supersonic Wind Tunnel (fig. 7). The wind tunnel installation is described in detail in reference 14. Inlet performance maps were obtained for various attitudes and angles of attack and several aft bypass door settings. Compressor face total pressure profiles, boundary layer profiles, static pressure distributions, and bypass calibrations were also obtained. The results are given in references 15 and 16.

As part of an effort to obtain accurate airflow measurements in flight, an engine airflow calibration was performed at Lewis Research Center's Propulsion Systems Laboratory. The engine that was installed in the aircraft for the research flights was calibrated with distortion screens that produced distortion patterns that simulated flight conditions. Over 3 percent degradation of performance in corrected engine airflow was observed from the previously used airflow characteristic curve that represents an average engine with little or no distortion. The results of these tests are discussed in reference 17.

Flight test results. - The flow sensing probe on the nose boom of the YF-12 airplane and the flow sensing tip of the YF-12 inlet centerbody were calibrated in the wind tunnel to insure flow conditions comparable to flight (ref. 18). Flight results for the local flow at the inlet spike tip over a wide range of flight conditions are given in reference 19. Local flow angularity, Mach number, impact pressure, and mass flow at the inlet spike tip are compared with free-stream values. Detailed descriptions of the YF-12C airplane, propulsion system, and instrumentation for propulsion research flights are given in references 20 to 22. Flight tests of the propulsion system included an investigation of off-schedule inlet operation. Some preliminary results are presented in reference 23. Analysis of the steady-state performance of the propulsion system is in progress. Additional flight test results can be found in reference 24.

Wind tunnel/flight comparisons. - To obtain a meaningful comparison between wind tunnel and flight data, similarity must exist in inlet geometry, test conditions, and instrumentation. References 25 and 26 discuss in detail the instrumentation requirements for flight-to-wind-tunnel comparisons. Preliminary results of comparisons between wind tunnel and flight data are given in reference 27. More recent comparisons of wind tunnel tests of 1/3- and full-scale models are made in reference 28. The performance comparison indicates that wind tunnel results can be a satisfactory indication of performance in flight if inlet conditions are matched. Further steady-state data are now being analyzed. The YF-12 overall propulsion system inlet performance is discussed in references 29 and 30.

Propulsion System Dynamic Performance and Inlet-Engine Compatibility

1/3-scale test results. - Large amounts of dynamic pressure data were acquired from the tests at Ames. These data included a 40-tube total pressure survey at the engine face, duct wall static pressures, and boundary layer total pressure rake measurements. The applicable data were stored on magnetic tape. Dynamic pressure data and a statistical analysis of selected pressure data are given in reference 12.

Full-scale test results. - The dynamic pressure data included a 24-tube total pressure survey at the compressor face which was identical to the installation for the flight tests. These data were recorded on magnetic tape for comparison with dynamic data to be obtained in future flight tests.

Flight test results. - Dynamic flight tests were performed that included deliberately induced unstarts and compressor stalls. An investigation of pressure data during an unstart is being performed to see if an unstart-induced stall is present in flight. Examination of dynamic data indicates that inlet-engine compatibility is good over most of the flight envelope (ref. 23). Since external disturbances can affect the stability margin of the propulsion system, the atmospheric effects on the inlet system were investigated.

Some preliminary dynamic flight distortion data were reduced on contract. The objective of the first phase of the work was to integrate the necessary hardware and computer software to make digital data processing possible. The objective of the second phase was to screen inlet dynamic data to extract those time slices during which engine face pressure distortion was most critical and to provide digital records of those events. In addition, duct pressure data were obtained during transient conditions. The data reduction method is operational, and some digital tapes of a limited amount of compressor face and duct pressure data are now being analyzed with a statistical program.

Wind tunnel/flight comparisons. - The currently available flight dynamic data cannot be compared with wind tunnel data because of zero shifts in the pressure data due to the severe temperature and vibration flight environment. The present wiring installation uses flexible wire that apparently allows zero shifts when the aircraft is operating in this severe environment. This wiring is being replaced with a steel-encased two-conductor cable which should eliminate the problem. After this installation, it should be possible to compare flight dynamic data directly with wind tunnel data.

Inlet and Engine Control Systems

Inlet control system. - The full-scale YF-12 flight hardware with the duct pressure ratio inlet control system was tested in the Lewis wind tunnel (ref. 31). These data served as a baseline for comparison with other shock position control systems. This investigation also demonstrated that a digital computer could be used to control a flight-type inlet and could provide all the schedules and other complexities required of an actual aircraft inlet control. Frequency response and transient testing of various experimental shock position controls are given in reference 32. Optimum shock position controllers of the proportional plus integral form were determined analytically and tested experimentally. Open loop dynamic wind tunnel data are given in reference 33, which evaluates the response of the flight inlet to internal airflow perturbation. External disturbances are difficult to simulate in the wind tunnel and are better investigated in flight. An electronic terminal shock position sensor was tested, and the results are given in reference 34.

Turbine inlet gas temperature control system. - Measurement of the turbine inlet temperature is useful in engine control because this temperature limits the maximum performance of the engine. This temperature has been unobtainable, because thermocouple and thermocouple support materials can not withstand a high temperature environment for long periods of time with the high reliability required for use in a control system. Hence, NASA, in conjunction with the Air Force, contracted the development of a high-response fluidic sensor for a turbine inlet gas temperature (TIGT) control system (refs. 35 and 36). The flight evaluation of this control system is complete and the data are presently being analyzed.

Stability bleed system. - A control concept that is presently being studied at Lewis is a stability bleed system that has been applied to the YF-12 inlet (fig. 4). Two sets of mechanical relief valves are arranged in the cowl. The bleed bypass opening is controlled by poppet valves and is scheduled as a function of the differential pressure between the bleed chamber and the reference volume. An orifice restricts the flow from the back side of each valve and thus dampens the effects of pressure fluctuations (ref. 37). The optimization of the cowl bleed hole pattern and steady-state testing of this stability bleed system has been completed. Dynamic testing of the valves in the YF-12 full-scale inlet at Lewis is also complete. Preliminary results indicate good performance of the valves, with increased stability margin for operation in the Mach 2.5 to 2.8 range (refs. 38 and 39).

Cooperative control system. - The cooperative control system as described in reference 40, is mechanized around a digital computer (fig. 5) that contains the control laws to process the inputs and generate the outputs. Figure 8 is a flow chart of the various segments of the cooperative control development. A major part of the effort involves the development of the simulation and software. It is planned to incorporate the control integration in logical steps, with optimal integrated control laws not incorporated until late in the program. One airborne digital computer has been purchased, and control laws are being synthesized on the simulator. More detailed discussions of this proposed control system are given in references 41 and 42. Other discussions of various aspects of the airframe/propulsion system interactions are given in references 43 to 47.

Airframe/Propulsion System Interactions

As part of the YF-12 performance and propulsion program, a limited amount of information was obtained on nacelle flow interaction to lay the groundwork for future flight testing. Surface pressure data were obtained from a 1/12-scale model tested at Ames, and a tuft study of the local flow around the nacelle of a YF-12 airplane was performed.

1/12-scale test results. - Wind tunnel tests of the 1/12-scale model have been run, primarily to obtain force data. A limited number of surface static pressure measurements were obtained during these tests. The pressure orifices were installed on the left wing and nacelle, and measurements were made with various bleed flows through the forward bypass and centerbody bleed louvers.

Subsequent testing was done with the same model to obtain loads data. Many additional pressure orifices were installed for these tests. Extensive data were obtained throughout the Mach number range and for various bleed flows. In addition, data for started and unstarted inlet conditions were recorded.

Finally, inlet flow field data were obtained by removing the inlet and placing a rotating conical probe in the plane of the cowl lip to evaluate the Mach number and angularity of the flow entering the inlet.

Flight tuft studies. - To obtain an understanding of the complex flow around the YF-12A inlet, tufts were placed on the inboard upper and lower quarters of the nacelle (ref. 24). High-speed cameras were used to record the flow directions indicated by the tufts during supersonic flights. Tuft movement and direction were obtained along with flow patterns from the film (fig. 6). Results were obtained for a wide range of flight conditions.

PROGRAM PLANS AND SCHEDULES

Present Program

The present YF-12 propulsion dynamics program (table 1) includes plans to obtain compressor face and duct dynamic flight data in order to compare these results to the wind tunnel data, determine the effect of atmospheric turbulence on inlet dynamics, evaluate causes and effects of unstarts, and evaluate predictive techniques for inlet transients. The propulsion program is to be followed by the cooperative control program (table 2).

Compressor face dynamics. - The objectives of these tests are to obtain dynamic compressor face and duct pressure data in flight and to compare these data with wind tunnel data. From these comparisons dynamic distortion scaling laws can be established. For these flight tests the flexible wire that was used for the dynamic pressures is being replaced by a rigid line to obtain accurate measurements in the flight environment. Other propulsion instrumentation for the flight tests is being repaired during this time. The flight tests are expected to include 24 dynamic total pressure probes and 40 duct static pressure probes that have frequency responses from steady-state to 500 hertz.

Boundary layer dynamics. - The objective of these tests is to obtain dynamic boundary layer pressure data to compare with the wind tunnel results. Four boundary layer rakes, each with several dynamic pressure probes, are to be positioned along the inlet duct with static pressure probes.

Atmospherically induced turbulence. - The objective of these tests is to measure and evaluate the effects of atmospherically induced turbulence on the dynamics of mixed-compression inlets. This information is needed for the aerodynamic design and control of inlets. The method involves the installation of an instrument package, such as a gust probe (as used on the YF-12-935 airplane), on the nose boom of the airplane to determine the upstream disturbances, such as free-stream turbulence and induced structural modes. The flight test is to be conducted by predicting and searching for turbulent flight conditions comparable to altitudes and Mach numbers of future supersonic transports. The long-range goal of this program is to develop and evaluate an instrument package that can be placed on various supersonic aircraft to obtain a large data base for the study of the effects of upstream disturbances.

Inlet transients. - Large-scale propulsion transients have adverse effects on aircraft stability and passenger comfort. A careful documentation of flight experience and a validation of prediction techniques are needed for future aircraft designs. The objectives of these tests are to evaluate the causes and effects of the unstarts that occur during the compressor face and boundary layer dynamic flight test program and to compare results to analytical prediction techniques for aircraft stability and control.

Cooperative control system. - The overall objectives of this program are to control airplane/propulsion system interactions, optimize total system performance, and evaluate the predicted system characteristics in flight. Strong interactions have been found to exist between engine and inlet, or between propulsion system and airframe, for supersonic aircraft, such as the XB-70, YF-12, and F-111 airplanes. Use of the cooperative control system to take advantage of favorable interactions and avoid or minimize unfavorable interactions could result in significant improvements in fuel consumption, range, performance, and structural weight.

The cooperative control program schedule is given in table 2. The program has two phases. In the first phase (fig. 9(a)), the existing analog air data system, autopilot, inlet control system, and autothrottle system are converted to digital control. An advanced autopilot with an autothrottle has been developed, and flight tests of the complete digital system are planned to validate the hardware and software. In the second phase (fig. 9(b)), the control systems are integrated by using control laws developed from models of the airplane's propulsion system and aerodynamics. Optimal control methods as well as classical methods are being used to derive the new control concepts. Flight tests are planned to validate the integrated control. A complete description of this program is given in reference 42.

Expected Technical Results

Propulsion system steady-state performance. - During the 8 months' aircraft down time between November 1975 and June 1976, considerable progress is expected in the analysis of steady-state data. Specific areas of analysis include steady-state inlet performance, steady-state inlet recovery and distortion, local inlet flow measurements, airflow performance and measuring techniques, and techniques for flight and wind tunnel comparisons of inlet performance.

Propulsion system dynamic performance. - The data reduction plan for dynamic performance is shown in figure 10. The flight data, 1/3-scale data, and full-scale data are to be digitized, and distortion parameters are to be calculated for selected wind tunnel/flight match points. The effects of boundary layer rakes, filters, record length, engine face rake configuration, and distortion indexes are to be investigated. The statistical characteristics of distortion indexes and boundary layer pressures should be evaluated and used to establish dynamic scaling laws for wind-tunnel-to-flight correlations. In addition, an analysis of inlet unstarts, inlet transients, and stalls is in progress.

Control systems. - The analysis of the results of the Lewis stability bleed system wind tunnel test is documented in reference 38. The flight evaluation of the TIGT control system is in progress. With the better sensing and control expected from the cooperative control system, current operational margins could be reduced, resulting in payload gains. With better matching of engine and inlet flow, and with improved center of gravity control, drag can be significantly reduced. In addition, cooperative control reduces aircraft transients caused by unstart and reduces air traffic control problems because of tighter flightpath controls. The results obtained from this program are to be documented in NASA and contractor reports.

Airframe/propulsion system interactions. - The 1/12-scale wind tunnel pressure data are being analyzed to investigate the critical factors affecting airframe/propulsion system interactions. In addition, the 1/12-scale flow field data have been reduced and are being compared to results obtained in flight. The flight tuft study of the local flow around the nacelle of the YF-12A airplane is reported in reference 24.

Proposed Future Programs

Propulsion test bed. - It is proposed that the YF-12 airplane be used as a propulsion test bed for evaluation of future propulsion concepts, such as turbofan ramjets, variable cycle engine concepts, and supersonic transport (SST) inlets. An illustration of how the YF-12 airplane could carry test bed experiments is shown in figure 11.

Test bed experiments offer several advantages. High risk concepts can be investigated since the experiment is independent of aircraft propulsion systems and has miminal influence on aircraft stability and control. In addition, full-scale models can be tested, actual temperatures and continuous variations in Mach number can be obtained, and realistic flow fields can be simulated.

Advanced shock sensing techniques. - New shock sensing concepts are being developed for use in control systems to operate the controls in a closed loop mode. Because of the lack of reliable sensors that function in the flight environment, current inlet control systems utilize a scheduled control rather than a closed loop control on the primary variable. The plan is to develop and evaluate fiber optronics and other types of sensors in ground facilities and in flight on a ride-along basis. These sensors can be incorporated with advanced control loops by using the cooperative control computer.

Shock stability bleed system. - The Lewis shock stability system is to be evaluated for effectiveness against atmospherically induced and internal airflow disturbances. Wind tunnels are presently limited in simulating atmospherically induced disturbances to test shock stability systems. It is necessary to demonstrate that the shock stability concept is feasible in a flight environment and that mixed-compression inlets can operate nearer peak performance with such systems. This program depends on the successful accomplishment of the program to define the effects of atmospherically induced turbulence on mixed-compression inlets.

Flight effects of annular nozzle noise suppressors. - Annular nozzles appear to be effective noise suppression devices for the SST. Forward velocity effects are needed, since most suppressor concepts lose effectiveness relative to predictive static performance. The plan is to install an annular nozzle on a J58 engine to investigate reductions in flyover noise for high pressure ratio engines. The J58 engine is of interest because its pressure ratio is higher than that of most modern engines and it is therefore more representative of SST engines.

Airplane performance and drag prediction. - Investigation of flight and wind tunnel data from the B-70 airplane program indicated several areas where additional research is required to predict the performance of vehicles of the SST type. These areas can be identified as drag polars at transonic speeds (fig. 12(a)), drag polars at supersonic speeds (fig. 12(b)), lift-curve slope at high supersonic speeds (fig. 13), and drag increment due to dumping propulsion system air overboard at off-design conditions. To investigate these subjects with the YF-12 airplane, it is necessary to obtain accurate in-flight measurements of performance, representative subscale models of the airplane, and accurate knowledge of the shape of the airplane in flight. The Dryden Flight Research Center has the capability for most of the desired in-flight measurements, and flexibility studies have already been performed on the YF-12-935 airplane. With the addition of various subscale models, the above problem areas could be investigated so that the technology could be available for a future SST.

CENTER RESEARCH AREAS

The YF-12 propulsion program is a cooperative program among the Ames, Lewis, and Dryden research centers. The nature of the program requires interdisciplinary expertise and facilities that do not exist at any single NASA center. The Dryden Flight Research Center manages and coordinates the overall program, including the YF-12 contracts, and performs all flight-related functions. Dryden is responsible for developing a cooperative control system for the YF-12 propulsion system. The Lewis Research Center conducts analytical studies on inlet designs, performs full-scale wind tunnel tests, and performs engine calibration tests. Lewis is also responsible for developing new control systems that could be applicable to flight hardware. The Ames Research Center is responsible for the analysis and design of wind tunnel models and the wind tunnel testing of these models. All three NASA centers are involved in the correlation of flight and wind tunnel data.

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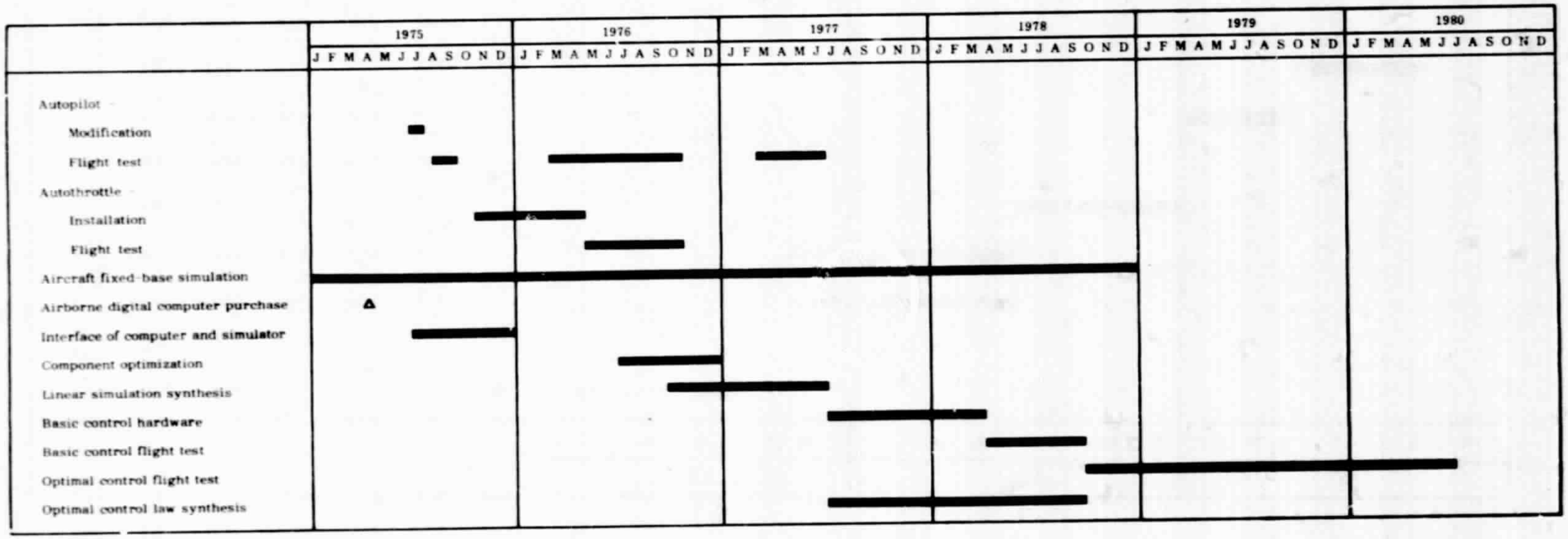
TABLE 1. PROPULSION DYNAMICS PROGRAM SCHEDULE

	1975												1976												1977											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
TIGT flight test			■				■	■																												
Compressor face dynamics -																																				
Transducer wire replacement											■	■	■	■	■	■	■	■																		
Instrumentation installation											■	■	■	■	■	■	■	■																		
Flight test																			■	■	■	■	■	■												
Boundary layer dynamics -																																				
Instrumentation installation																									■	■	■	■								
Flight test																													■	■	■	■	■			
Atmospherically induced turbulence -																																				
Gust probe installation																									■	■										
Flight test																													■			■				

TABLE 2. COOPERATIVE CONTROL PROGRAM SCHEDULE



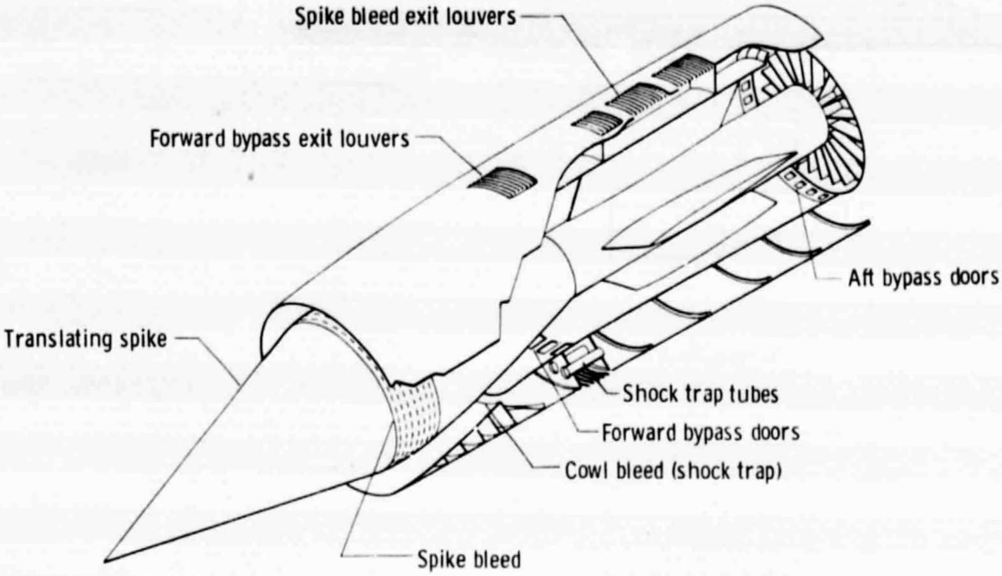


Figure 1. YF-12 inlet.

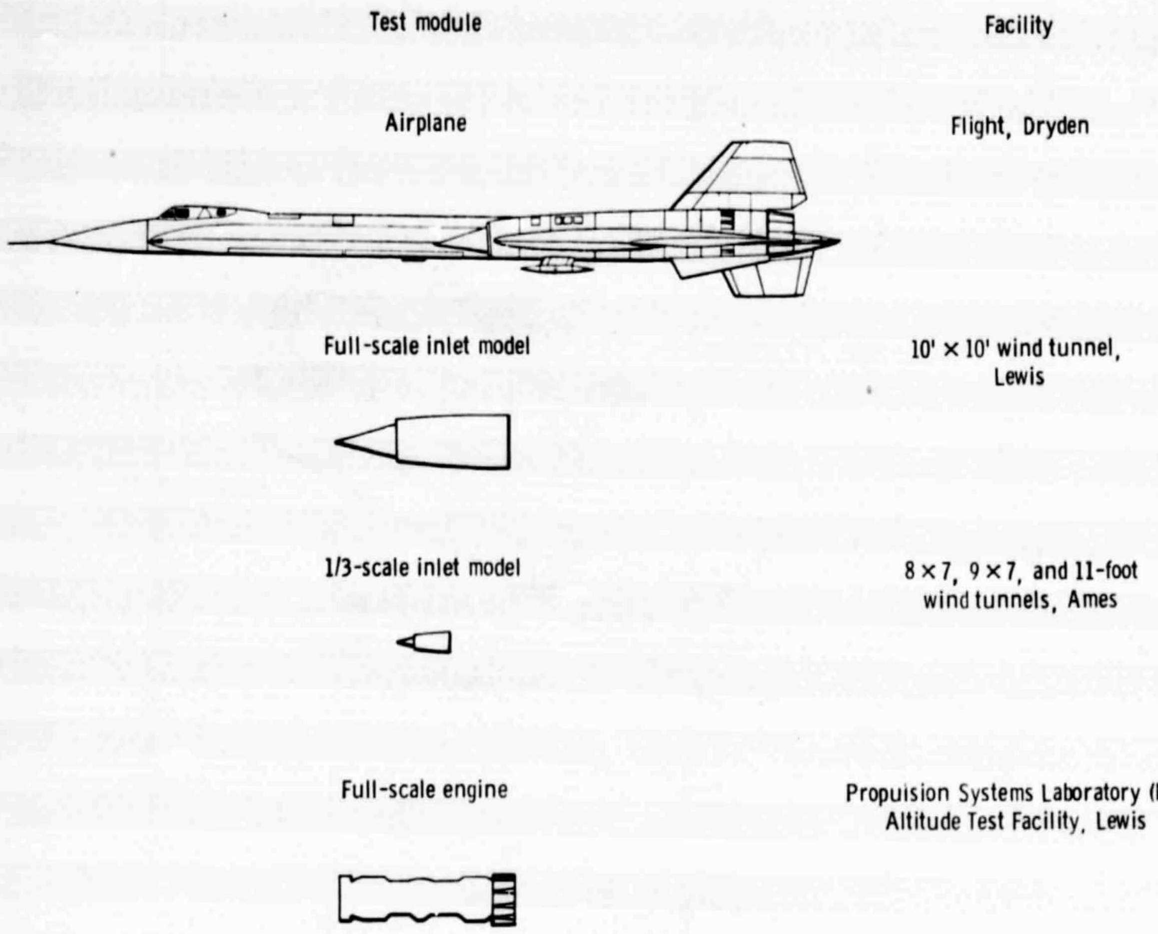
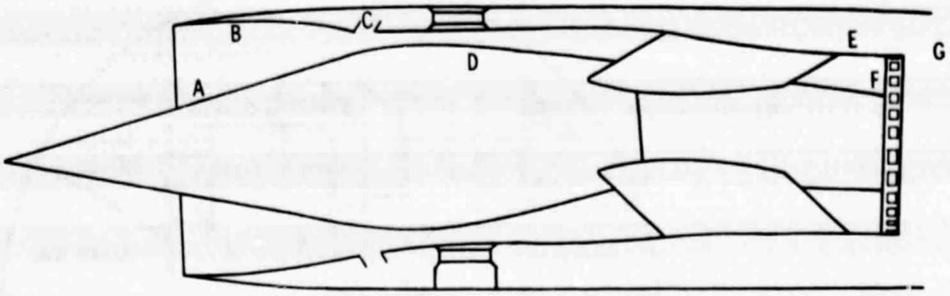


Figure 2. Comparison of inlet configurations and facilities.



NASA Research Center	Scale	Type	Location of pressure sensors							
			A	B	C	D	E	F	G	Total
			Number of sensors							
Ames (wind tunnel)	1/3	Steady state	73	32	84	44	47	40	-	320
		Dynamic	12	6	16	12	1	40	-	87
Lewis (wind tunnel)	Full	Steady state	75	58	128	94	45	52	-	402
		Dynamic	-	11	27	-	12	24	-	74
Dryden (flight vehicle)	Full	Steady state	9	17	33	8	13	50	3	133
		Dynamic	4	4	19	6	6	24	3	66

Figure 3. YF-12 inlet study instrumentation comparison.

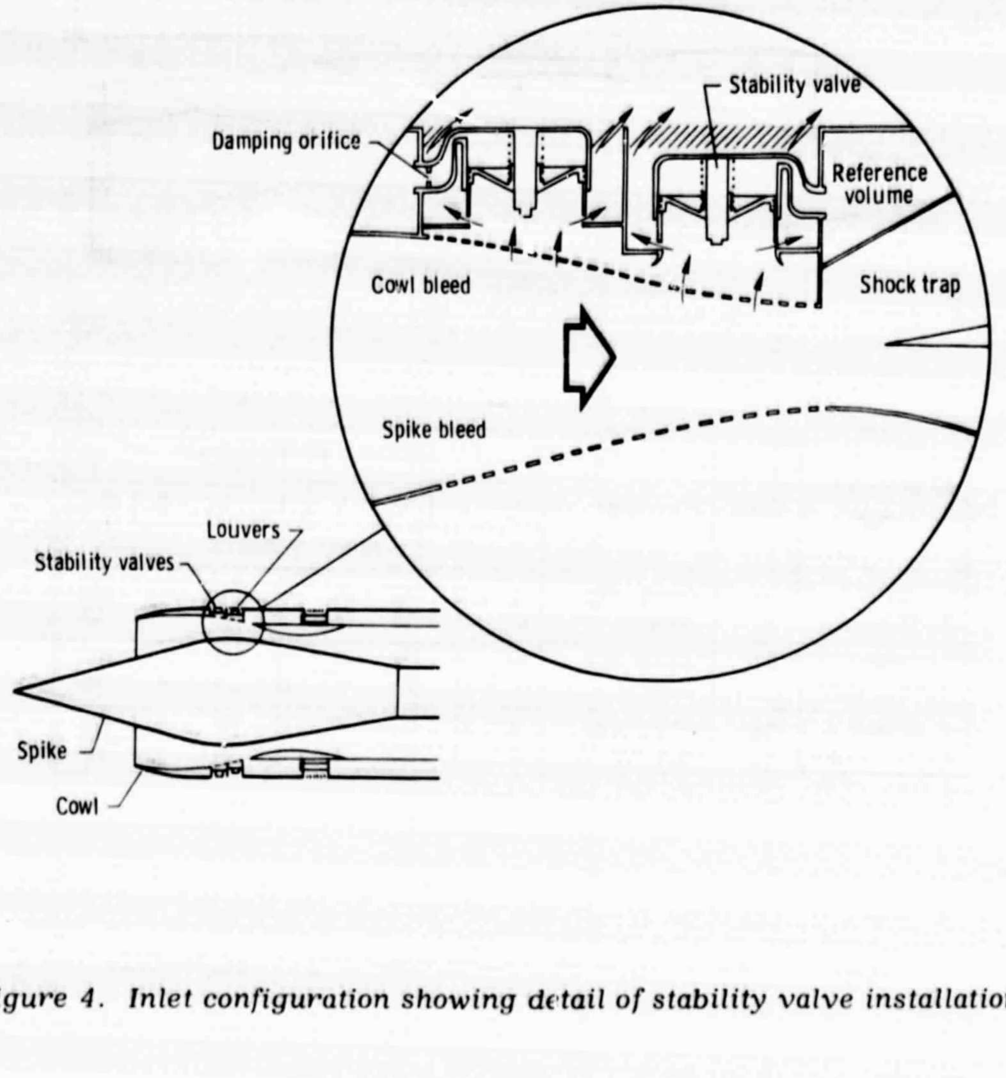


Figure 4. Inlet configuration showing detail of stability valve installation.

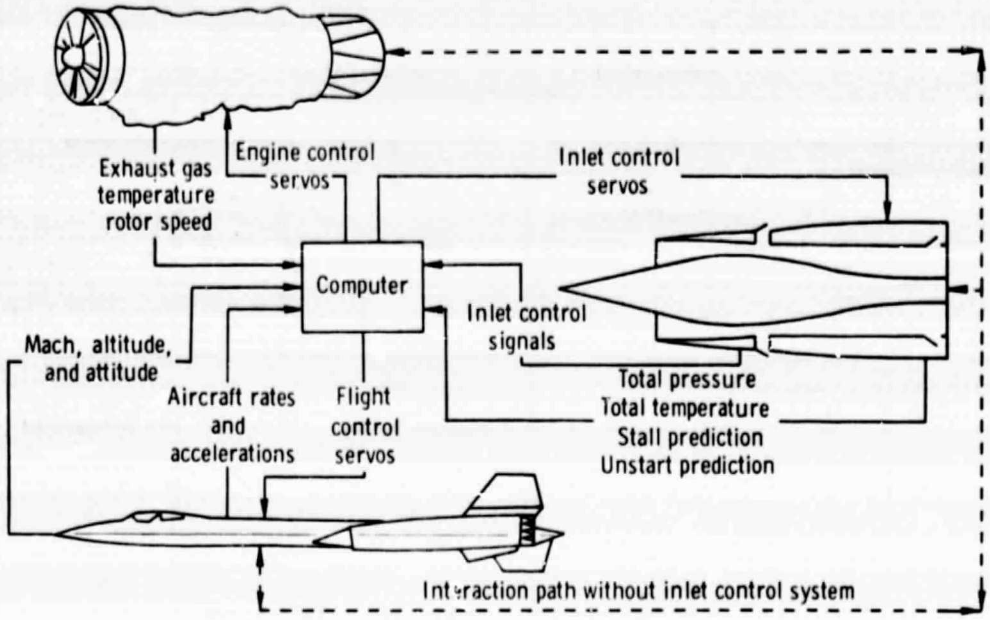


Figure 5. Conceptual schematic drawing of an integrated control system.

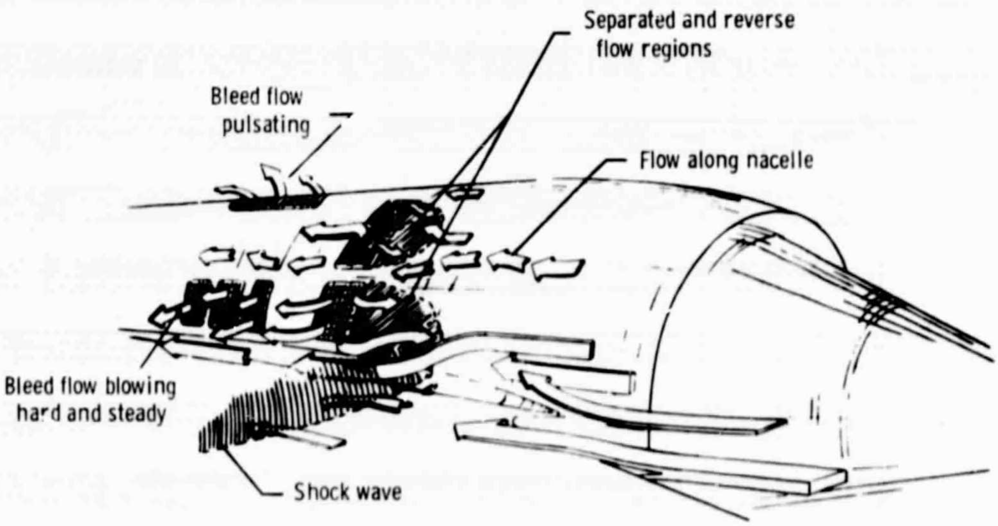
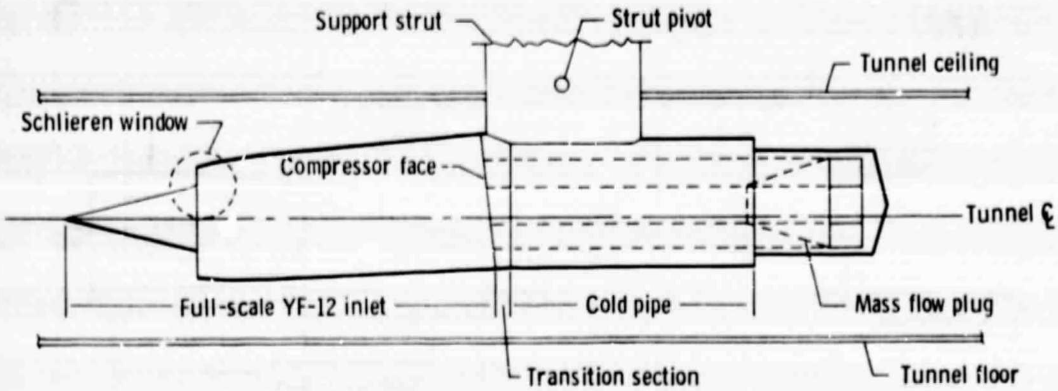
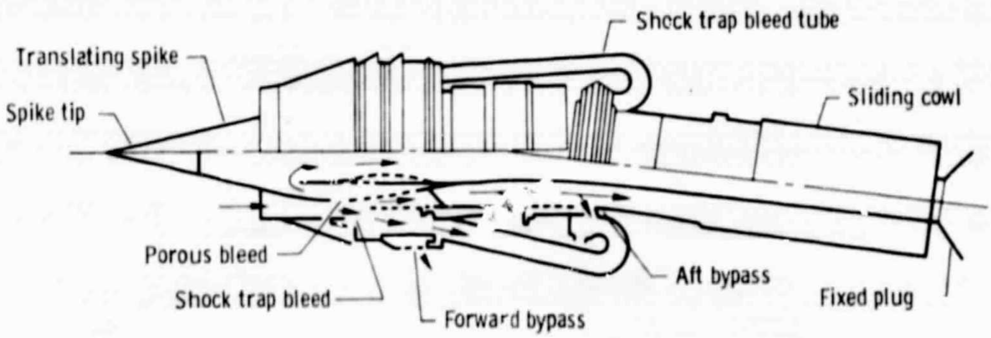


Figure 6. Tuft study for high supersonic Mach number operation. Forward bypass door open.



(a) Full-scale model, Lewis 10' X 10' tunnel.



(b) 1/3-scale model, Ames Unitary Tunnel Facility.

Figure 7. Wind tunnel inlet models.

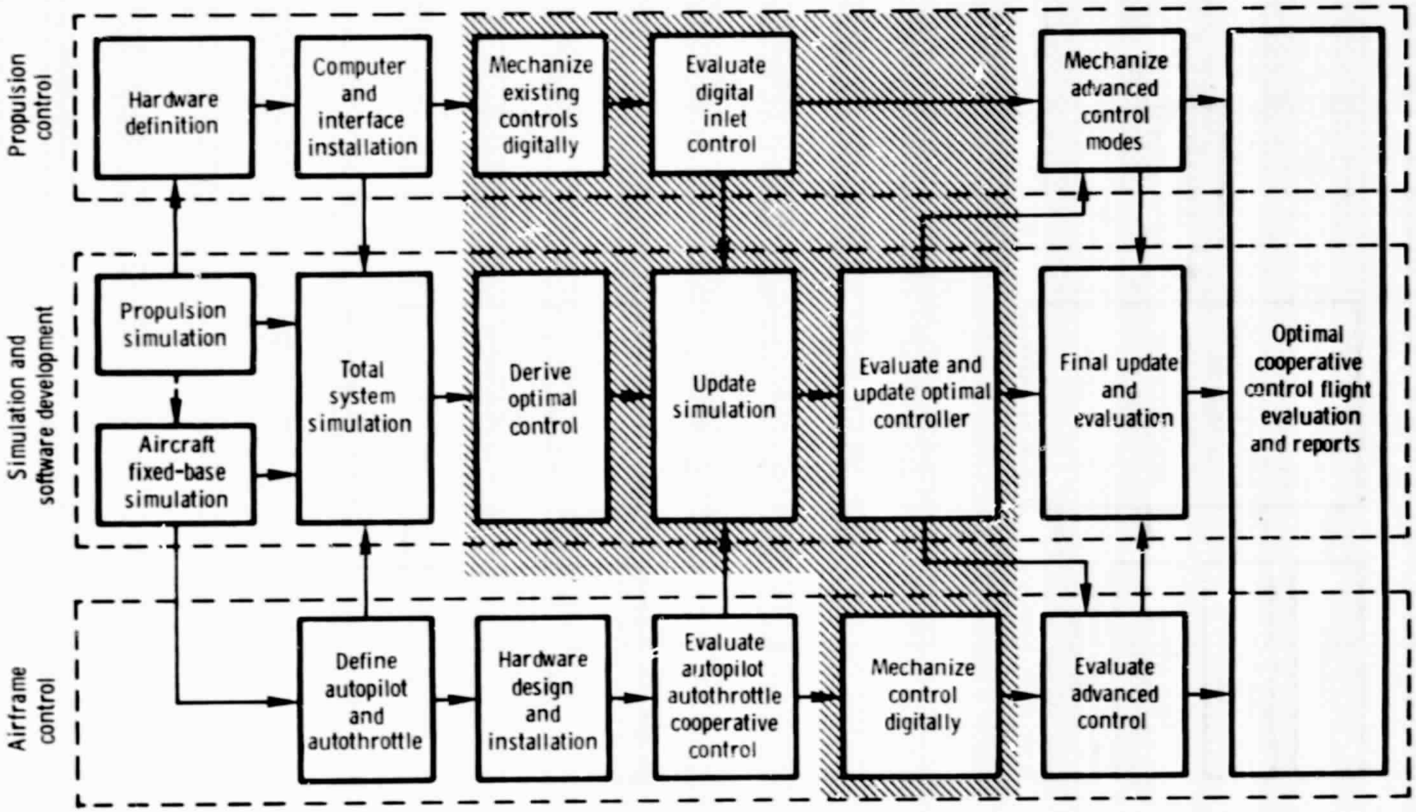
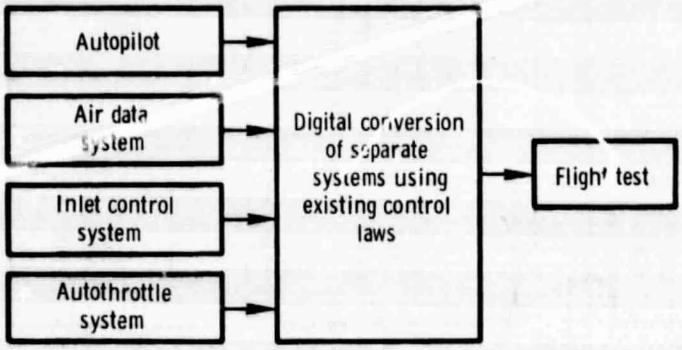
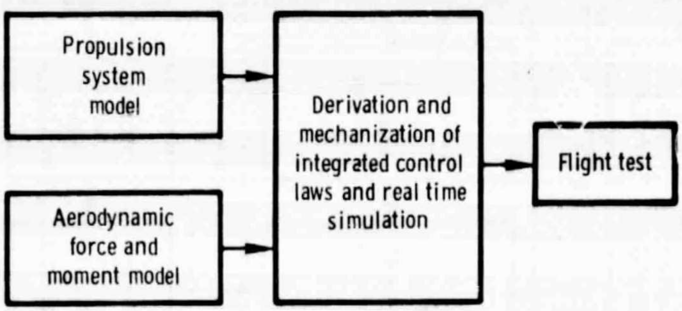


Figure 8. Cooperative control program.

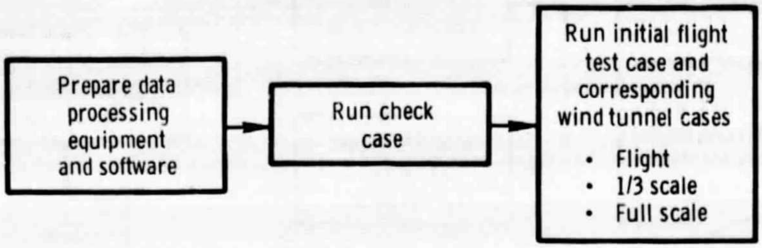


(a) Phase I.

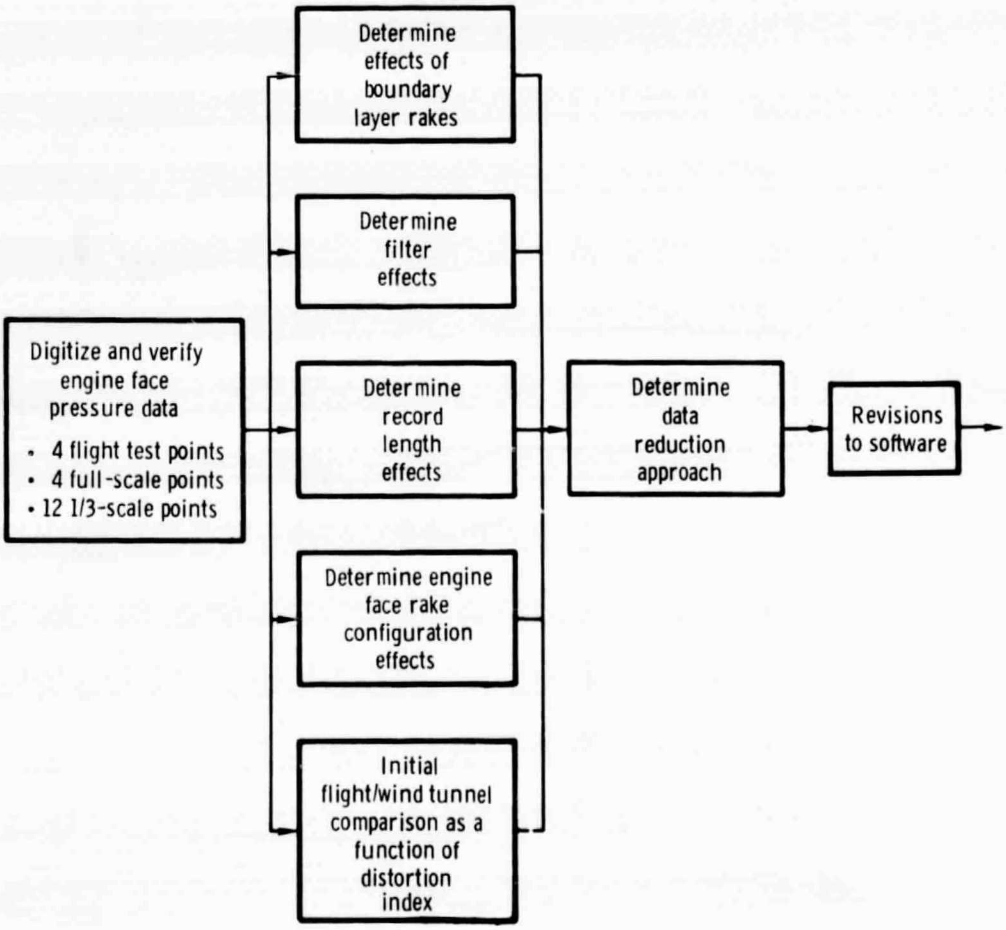


(b) Phase II.

Figure 9. Cooperative control program.

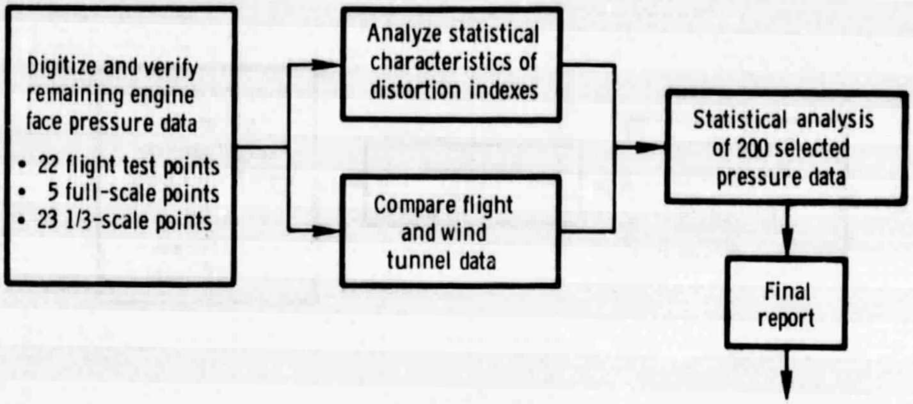


(a) Phase I.



(b) Phase II.

Figure 10. Work flow schematic.



(c) Phase III.

Figure 10. Concluded.

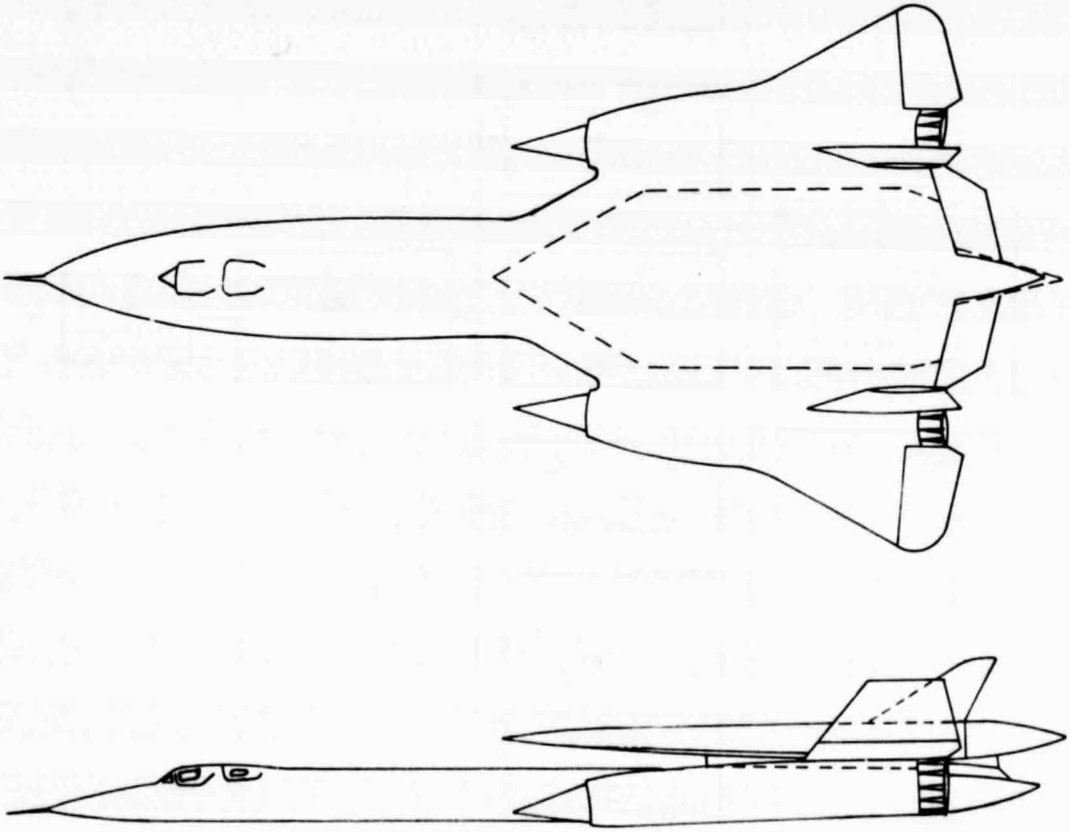
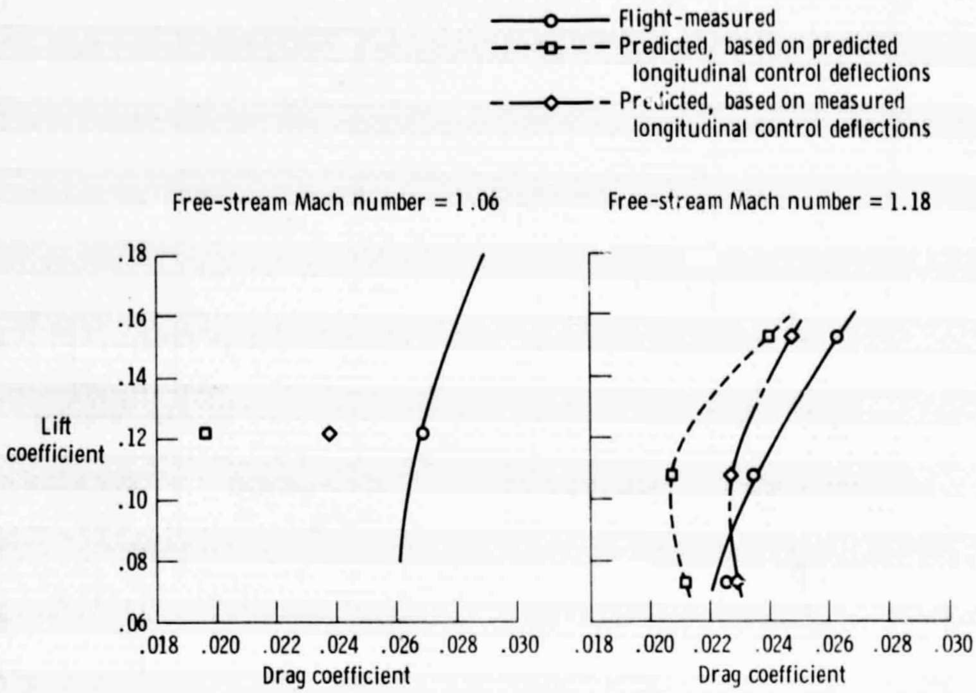
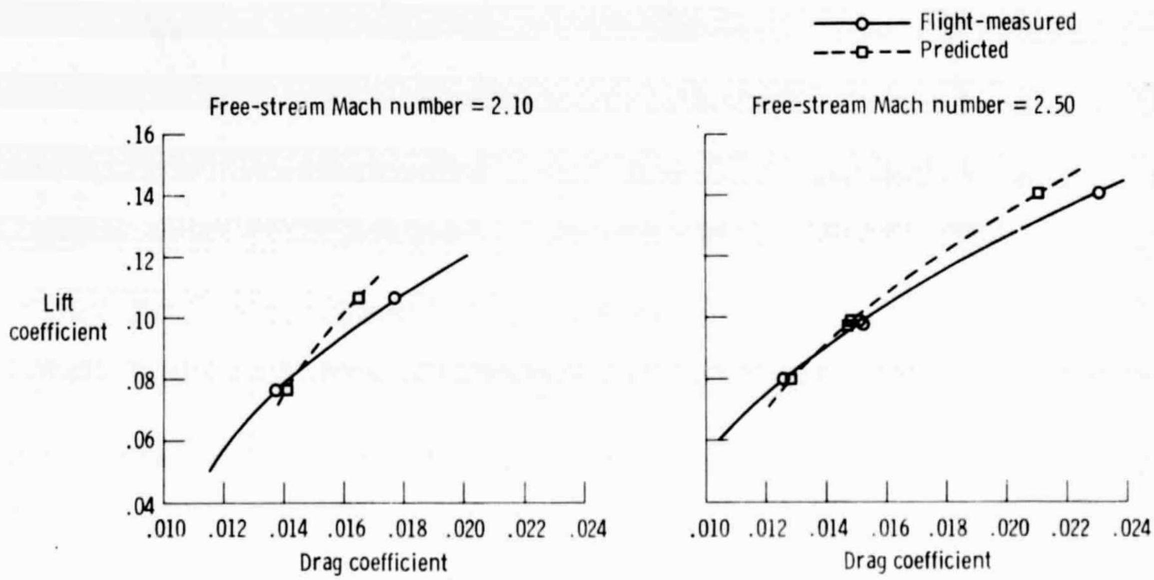


Figure 11. YF-12 airplane as test bed.



(a) Transonic speeds.



(b) Supersonic speeds.

Figure 12. Comparison of flight-measured and predicted drag.

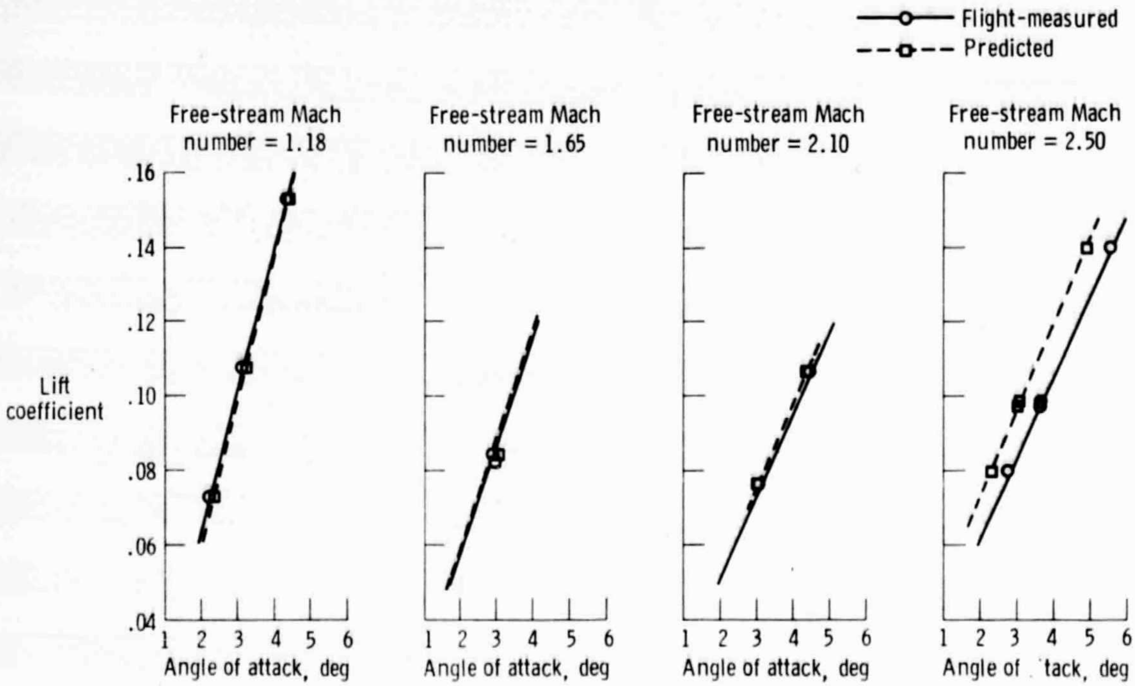


Figure 13. Comparison between flight-measured and predicted angle of attack.