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POTENTIAL BENEFITS OF PROPULSION AND FLIGHT CONTROL INTEGRATION FOR SUPERSONIC CRUISE VEHICLES*

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SUMMARY

Supersonic cruise aircraft can exhibit strong interactions between the propulsion system and the airframe. These interactions can be aggravated or improved by the behavior of the propulsion control system and the flight control system. When these controls are designed independently, they tend to affect the interactions adversely. When the propulsion and flight controls are integrated, however, the benefits can be synergistic.

This paper reviews typical airframe/propulsion interactions such as Mach/altitude excursions and inlet unstarts. The improvements in airplane performance and flight control that can be achieved by improving the interfaces between propulsion and flight control are estimated. A research program at the NASA Flight Research Center to determine the feasibility of integrating propulsion and flight control is described. This program includes analytical studies and YF-12 flight tests.

INTRODUCTION

Interactions between airframes and propulsion systems go back to the earliest history of powered aircraft. Along with the stories of daring aviators in open cockpits, we also heard of large rolling moments due to rotary engine torque and yawing moments induced by propeller slipstream. Interactions such as these were handled in a straightforward manner by applying large amounts of lateral stick and rudder control. The introduction of jet engines at first alleviated these interactions. However, as flight speeds increased, propulsion systems became more complex and sophisticated. A typical supersonic cruise aircraft has an inlet with variable geometry features programed by engine, inlet, and airframe variables. These propulsion system features influence the thrust, drag, performance, stability, and control of the entire vehicle. Efficient utilization of these interactive effects could greatly enhance the overall effectiveness of a supersonic cruise vehicle. To accomplish this, the engine, inlet, and flight controls must be integrated so that they work cooperatively for optimum vehicle performance.

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*Based on SAE paper 740478, 1974.

This paper describes the principal types of interaction phenomena that have been encountered in NASA flight research (refs. 1 and 2) and proposes approaches and solutions to interaction problems. It discusses the potential benefits of integrating propulsion and flight controls into a cooperative airframe/propulsion control system and describes a research program to determine the feasibility of the system and to demonstrate it in an operational environment.

SYMBOLS

BPD	bypass door opening, percent of full open
g	acceleration due to gravity, m/sec^2
I_X, I_Z	moment of inertia about the X- and Z-body axes, respectively, kg-m^2

$L = 57.3 \dfrac{\text{Rolling moment}}{I_X}$, deg/sec^2

$L_{unstart} = 57.3 \dfrac{\text{Rolling moment due to unstart}}{I_X}$, deg/sec^2

$N = 57.3 \dfrac{\text{Yawing moment}}{I_Z}$, deg/sec^2

$N_{unstart} = 57.3 \dfrac{\text{Yawing moment due to unstart}}{I_Z}$, deg/sec^2

δ_a	aileron deflection, percent of maximum deflection
δ_r	rudder deflection, percent of maximum deflection
ζ	Dutch roll damping
ω_d	Dutch roll damped natural frequency, rad/sec
ω_n	Dutch roll natural frequency, rad/sec

Subscripts:

BPD, δ_a, δ_r	partial derivatives with respect to subscripted variable
max	maximum

DESCRIPTION OF INTERACTIONS

The types of interactions to be discussed are shown in figure 1, in which the flight vehicle is considered to consist of three elements: airframe, engine, and inlet. Many interactions are possible between these elements, and all possible combinations have probably occurred, at least to a minor extent. The figure illustrates three typical types of interactions that have been observed during NASA flight research: (1) the F-104 airplane interactions primarily involve the airframe and the inlet; (2) the F-111 airplane interactions are primarily between the engine and the inlet; and (3) the XB-70 and YF-12 airplane interactions, which are typical of supersonic cruise aircraft with mixed-compression inlets, primarily involve the airframe, inlet, and engine.

A prime example of an airframe/inlet interaction, shown in figure 2, was observed during the development of an F-104 airplane. Uncontrolled airplane motion began when the pilot initiated a left roll at Mach 1.87 (time = 0.8 sec), which caused the airplane to sideslip. This precipitated an engine surge at time = 2.5 seconds, which resulted in an engine mass flow reduction. A detailed analysis (ref. 3) showed that this reduction in mass flow forced the inlet shock forward on the lee side of the fuselage, creating a higher yawing moment in the opposite direction. The phase relationship to the natural frequency of the airplane was such that the vehicle's oscillations were divergent. After one-half cycle of the oscillation, the throttle was retarded to prevent an engine overtemperature which could have resulted from the surge. This power change further aggravated the yawing motion by reducing the mass flow through the inlet and causing the sideslip to exceed the 2° limit of the airplane.

The angle-of-attack excursions shown in figure 2 represent a pitching oscillation of 1.5g to 2.0g. The left and right side inlet recovery indicates the magnitude of the inlets' active participation in the motion. The interaction was eliminated on subsequent flights by extending the splitter plate between the left and right side inlets back to the compressor face, as shown in the sketch. This reduced the crossflow between the two inlets that had caused the shock motions.

The F-111 airplane is an example of an interaction primarily between the engine and the inlet (ref. 4). A time history of a dynamic interaction on the F-111A airplane is shown in figure 3. These data were obtained during stabilized flight and constant power setting at a Mach number of 2.17. The dynamic distortion of the inlet initially oscillated within the stall limits but finally peaked above the boundary, resulting in an engine stall and an aborted flight. No significant airframe interactions induced by the engine or the inlet were noted during the NASA flight tests of the F-111 airplane in which more than 100 engine stalls were experienced throughout the flight envelope.

For maximum efficiency, supersonic cruise vehicles usually have a mixed-compression inlet, that is, an inlet in which the normal shock is in the throat rather than outside the cowl lip. This provides the highest inlet recovery and the best range for a point design aircraft. However, if the normal shock is disturbed and moves to a position forward of the throat, it can become unstable and "pop" out of the inlet. This phenomenon is called an unstart. High pressure air from the inlet is suddenly discharged, causing massive flow disturbances over the external surfaces of the aircraft as well as inside the inlet. This results in strong interactions between the engine, inlet, and airframe. Figure 4 is a time history of a double unstart that occurred during a turn at Mach 3 with the XB-70 airplane. The unstart was believed to have been initiated by a minor disturbance in the left inlet. The right duct unstarted approximately 11 seconds after the left duct as a result of intervening airplane motions. The change in pressure under the left wing, caused by the expulsion of the normal shock forward of the inlet lip, increased the normal acceleration. The normal acceleration was further increased by the opening of the bypass doors, which acted essentially as elevons. The pilot countered this pitching motion with a longitudinal control input of approximately 3° nose-down elevon. The unstart and door movements also affected lateral control, causing the airplane to roll toward the side that had unstarted. The pilot's corrective action prevented the roll rate from becoming large, but bank angle changed noticeably. From the magnitude of the pilot's inputs to prevent the pitching and rolling motions, it was estimated that the unstart pitching and rolling moments would have produced a 2.5g steady-state acceleration and a 30-degree-per-second roll rate. Similarly, loss of thrust, increased spillage drag, and the opening of the bypass doors during the restart cycle caused a longitudinal deceleration of approximately 0.1g. Perhaps even more significant to a passenger on a supersonic transport would be the rate of onset of acceleration, which was nearly a 0.1g step function.

Additional appreciation for these interactive forces is provided by the following YF-12 data (ref. 2) which show the relative magnitudes of the accelerations produced by an unstart and the aerodynamic controls:

$$L_{unstart} = 3.3 \text{ deg/sec}^2 \qquad N_{unstart} = 6.4 \text{ deg/sec}^2$$

$$L_{\delta_a}\delta_{a_{max}} = 30.4 \text{ deg/sec}^2 \qquad N_{\delta_r}\delta_{r_{max}} = -7.3 \text{ deg/sec}^2$$

The effectiveness of the bypass doors in producing yawing and rolling accelerations during normal inlet operation at Mach 3 is shown by the following derivative equations (ref. 2):

$$L_{BPD} = 0.35 \frac{\text{deg/sec}^2}{\text{percent BPD}_{max}} \qquad N_{BPD} = 0.11 \frac{\text{deg/sec}^2}{\text{percent BPD}_{max}}$$

$$L_{\delta_a} = 0.295 \frac{\text{deg/sec}^2}{\text{percent } \delta_{a_{max}}} \qquad N_{\delta_r} = 0.073 \frac{\text{deg/sec}^2}{\text{percent } \delta_{r_{max}}}$$

The propulsion system is as effective as the aerodynamic control surfaces in producing angular accelerations. Also, the significant rolling accelerations produced by the bypass door operation indicate that the moments are not produced only by thrust changes, because the YF-12 airplane has no thrust moment arm about the roll axis.

It is important to recognize that the interaction problem is not just one of stability and control. Interactions can also seriously affect the drag and range performance of an airplane. Figure 5 shows the effect of asymmetric bypass door opening at Mach 3 on the YF-12 airplane drag increment expressed as a percentage of the basic airplane drag, the vertical fin deflection from the trimmed condition, and the mass flow out of the bypass doors. Fully opened bypass doors cause a 25-percent increase in drag (per engine) and require 15 percent of the rudder authority to maintain zero sideslip. At smaller door openings, a 10-percent change in mass flow out of a single bypass door causes a 2.5-percent increase in drag. As the bypass doors open beyond 40 percent, the mass flow out of the doors levels off because of a flow choking effect. The similarity of the drag and rudder deflection curves to the airflow curve indicates that bypass airflow is the primary cause of the interactions.

The coupling discussed has been primarily the result of direct or open-loop interactions. A modern aircraft, however, has numerous artificial sensing and feedback loops to implement a variety of control tasks. Consequently, closed-loop interaction paths can be formed that magnify the open-loop effects or create new coupling effects. An example is shown in figure 6. The YF-12 inlet computer modulates the bypass door movement as a function of sideslip (among other parameters) to minimize unstarts. Because of the influence of the fuselage, the flow at each inlet is not the same at a given sideslip angle. Consequently, the bypass doors are modulated asymmetrically, which produces yawing moments. As the block diagram indicates, these yawing moments cause the aircraft to sideslip. The sideslip is sensed by the inlet computer, which commands bypass door changes that produce further yawing moments. Thus a closed-loop path is formed that couples the propulsion system and the airframe. Because of lags in the inlet computer sensing system, this coupling is unstable (ref. 5), and when the stability augmentation system (SAS) is turned off while the inlets are operating automatically, an unstable Dutch roll motion results. As illustrated in figure 7, when the inlets are fixed, the Dutch roll motion damps out, but when the inlets are operating automatically, the Dutch roll motion diverges.

Another example of closed-loop airframe/propulsion coupling is inlet control as a function of Mach number. As Mach number increases, the YF-12 inlet computer closes the bypass doors, decreasing drag and increasing thrust; however, this changes the variation of excess thrust with Mach number. The long-period longitudinal motion, or phugoid, is sensitive to variations of excess thrust with Mach number. Increases in excess thrust with Mach number reduce phugoid damping, as illustrated in figure 8, which shows the controls-free altitude response of the YF-12 airplane to drag disturbances with the inlets fixed and the inlets operating automatically. The decreased damping of the motion with the inlets operating automatically, in response to Mach number, is apparent. The large overshoot and oscillations make flightpath control difficult.

PREDICTION

As the previous discussion indicates, the nature and magnitude of airframe propulsion interactions were learned from flight tests; they were not predicted. To achieve a basic solution to these problems, however, we must be able to predict the interaction effects so that they can be considered from the beginning of the vehicle design. As part of the YF-12 research program, wind tunnel tests were made to determine how detailed the model inlet geometry and airflow would have to be to provide data from which the interaction phenomena could be predicted adequately.

Our first effort in evaluating prediction techniques was to qualitatively assess the similarities of the local flow in the wind tunnel and in flight. In the wind tunnel, oil was placed on a 1/12-scale model of the YF-12 airplane which had been modified to simulate the bleed and bypass exits. The exits were slotted so that the flow was expelled at a 15° angle relative to the nacelle surface, and the bypass exits were fitted with screens to meter the flow. The mass flow out of the bleed and bypass exits was varied by changing the position of a butterfly valve in the inlet. The results of the oil flow tests are shown in figure 9, which indicates large areas of separated flow forward of the bleed and bypass exits on the nacelle and extending to the wing. Because the bleed and bypass exit simulation was not exact, it was questioned whether this represented the flow on the airplane. The exit louvers and the surrounding area of the nacelle and wing on the flight vehicle were tufted, and cameras for photographing the tufts were installed in the fuselage. Bleed and bypass mass flow ratios similar to those used in the wind tunnel were then evaluated in flight.

Figure 10 is a sketch of the flow field shown by the tuft pictures. The separated regions indicated by the wind tunnel oil flows are verified by the reversed flow forward of the bypass exits and the vertical standing tufts at the forward edge of the separated regions and on the bleed exit louvers. Thus it is expected that when all the wind tunnel data have been analyzed, the results will agree reasonably well with the flight-test data even though the exit simulation was not precise. Force and moment tests were also made on a 1/12-scale model with simulated inlet airflow. The results of these tests indicate that the forces and moments due to the propulsion system can be adequately predicted if the propulsion system is represented in sufficient detail.

Although it appears that wind tunnel data can adequately predict full-scale flight results, a general theoretical approach for predicting these aerodynamic effects is lacking. Nevertheless, by using wind tunnel tests and analytic techniques, mathematical models can be formulated for simulating and analyzing airframe/propulsion system coupling problems. Care must be taken to include all the elements that contribute to the interactive effects.

POTENTIAL BENEFITS

By using adequate simulation or analytical models, or both, that represent the entire system in the frequency range of interest, design trade-off studies can determine the advantages of integrated or cooperative controls. Many aspects must be considered in such a trade-off. For example:

(1) Should the vehicle be designed to eliminate interactions? What would be the penalty?

(2) Can the interactions be made favorable?

(3) Is it more efficient to control the interactions with systems than to redesign the vehicle configuration?

Although these considerations are only a few of the many that must be taken into account, they are typical and will be discussed briefly to provide some insight into the problems.

Should interactions be designed out of the vehicle? One way to reduce interactions is to bypass air entirely within the nacelle. However, this requires a larger nacelle diameter which, for the YF-12 airplane, would increase the nacelle drag by approximately 25 percent. Therefore it appears that it would be better to control the interactions with cooperative engine/inlet flight controls. This might mean increased demands on systems in terms of reliability and complexity; however, the penalties in range, payload, and performance would be much less than those resulting from increasing the size of the nacelle.

Ideally, the interactions would be arranged to be complementary. This could perhaps be done by careful placement of bypass exits or by means of the control laws in a system approach. As previously discussed, a time lag in the sideslip sensor for the inlet computer resulted in a decrease in Dutch roll damping; however, the basic interaction was favorable, in that it increased Dutch roll static stability, that is, increased frequency.

Figure 11 shows the variation of Dutch roll frequency and damping as a function of sideslip sensor lag and inlet-induced yawing moment for a YF-12 type of configuration. It can be seen that Dutch roll stability can be improved by increased lead in sensing sideslip and increased yaw due to bypass door deflection. This illustrates that the potential exists for using airframe/propulsion control integration to augment the stability of the airplane, reduce the need for more redundant and complex systems, and even reduce the size of the aerodynamic stabilizing surfaces. The increased frequency and damping would make the airplane more resistant to sideslip excursions and allow the inlets to be designed with lower sideslip margins and thus higher efficiency. Also, performance degradation due to turbulence might be reduced, since increased airframe frequency and damping would minimize gust response. These benefits could be gained without increasing the tail size or the control system complexity.

The critical design factor that determines the size of the vertical tail on a supersonic cruise vehicle is usually control of the aircraft in response to the moments induced during an inlet unstart at maximum Mach number. An integrated control system that would reduce unstart transients through propulsion control as well as aerodynamic control could result in significant reductions in tail size and commensurate weight and drag savings. Automatic spike, bypass, and throttle activity on the other nacelles and fast unstart recovery could greatly reduce the yawing and rolling moments and longitudinal decelerations associated with an unstart.

Difficulties are often experienced with conventional autopilots in the Mach hold mode when an atmospheric temperature disturbance is encountered (ref. 6). The temperature change induces an immediate Mach number change, and the autopilot commands large normal acceleration or altitude changes, or both, in an attempt to hold Mach number. Recent studies have shown that simple cooperation between the propulsion and flight controls through an autothrottle provides much smoother and more accurate response. This is illustrated in figure 12 which shows the altitude, Mach, and dynamic pressure excursions induced by a Mach hold autopilot with and without an autothrottle in response to a 4° C atmospheric temperature change. Shown is the response of a conventional Mach hold system in which pitch angle and Mach number are fed back to the elevons, and the response of a system with an autothrottle in which pitch angle is fed to the elevons and Mach number is fed to the throttles. The significant reduction in the altitude excursions with the autothrottle system is evident, whereas Mach control is essentially equivalent. The autothrottle system shows the potential for a 0.60-kilometer reduction in altitude separation for air traffic control purposes.

The altitude excursions in figure 12 are accompanied by overshoots in dynamic pressure. A supersonic airplane usually cruises most efficiently at the highest dynamic pressure. The maximum dynamic pressure allowable for normal operation is based on the dynamic pressure limit of the airplane (for structural reasons) plus a suitable margin to allow for unintentional overshoots. The figure shows that the autothrottle reduces the dynamic pressure overshoot by 3200 N/m^2. This implies that the airplane could be operated safely at a correspondingly higher dynamic pressure, which amounts to approximately a 1-percent increase in cruise range.

Performance gains that may be realized by using a cooperative control system in a vehicle similar to the YF-12 airplane are summarized in the following table:

	Payload gain, percent of airplane gross weight
Margin reduction —	
Inlet stability	1.8
Engine temperature	2.0
Altitude control	1.0
Drag reduction —	
Propulsion system	1.25
Trim	0.70
Structural weight reduction —	
Ventral fin	0.40

If the inlet could be operated with minimum unstart margins (that is, with the shock at the throat rather than downstream), as much as a 5-percent increase in thrust could be realized. This translates into a 1.8-percent improvement in payload in terms of airplane gross weight. Similarly, improved sensing and control of the turbine inlet temperature rather than the low response turbine discharge temperature could produce more than a 5-percent increase in thrust or 2.0 percent in payload. Studies have indicated that the elimination of ±600-meter altitude excursions would allow approximately 1.0 percent increase in payload.

Drag reductions could be realized by better matching of the inlet and engine flows through use of engine speed control to vary the airflow at off-design operating conditions of atmospheric temperature and aircraft speed. Reduced unstart transients and improved flight control could make possible reduced aircraft stability margins, with a resultant payload benefit of approximately 0.70 percent for trim drag reduction and 0.40 percent for decreased vertical fin weight. Although the individual gains listed may not be directly additive, they represent approximately 7 percent of the gross weight of a typical supersonic cruise airplane. If cooperative control concepts were incorporated into the original design of an airplane, the benefits could be even greater because of the synergistic savings in structural weight which have not been considered in this analysis.

DESIGN APPROACH

The magnitude of the problem of integrating the autopilot, stability augmentation, inlet, and engine can be illustrated by the matrix of control options shown in figure 13. State variables of the airplane, inlet, and engine can be fed back to each control. Typical state variables include:

Airplane - angular and linear velocities and accelerations, Mach number, altitude, angle of attack, angle of sideslip

Inlet - shock position, recovery, distortion

Engine - rpm, compressor face pressure and temperature, turbine discharge pressure and temperature

Typical controls include:

Autopilot - elevons, rudders, servo positions

Inlet - bypass door and spike position

Engine - power lever angle, exhaust nozzle position, fuel metering valve

A fully integrated control system would include at least one state variable feedback to each control, as indicated by an X in each square of figure 13(a). In contrast, figure 13(b) represents a system with no integration; that is, there is no communication or cooperation between the airplane, inlet, and engine controls. Between these extremes, varying degrees of integration are possible, as illustrated in figures 13(c) and 13(d). Figure 13(c) is representative of the existing YF-12 airplane, in that some airplane states such as angle of attack, angle of sideslip, and Mach number are used to control the inlet. Figure 13(d) could represent a YF-12 airplane with an autothrottle that used Mach number to control the power lever angle. Just how far to go in the integration process will depend on many practical as well as theoretical considerations.

Integrating all these diverse and complex factors is a formidable task. Classical approaches based on experience and engineering judgment have been used. If there is a high degree of interdisciplinary coordination, classical feedback techniques may be adequate. The most promising approach, however, may be based on optimal control techniques. This approach generally involves feeding back all state variables and computing the control system gains required to minimize an appropriate performance penalty function.

When both classical and optimal control approaches have been applied to the same problem, the results have usually been the same. It should be kept in mind, however, that the classical techniques depend on analysts and designers with many years of applicable experience. When dealing with new phenomena involving complex interdisciplinary effects such as airframe/propulsion coupling, it may be difficult or impossible to find people with adequate backgrounds and practical experience to handle a classical approach. Conversely, the optimal control technique provides a systematic approach that can be used when there is little insight into the problem.

ONGOING RESEARCH

To explore and validate the benefits that could result from a cooperative control system, analytical and flight research is underway at the NASA Lewis and Flight Research Centers. The objectives of this effort are to determine the feasibility and advantages of a cooperative autopilot/SAS/propulsion control system and to verify and demonstrate the benefits of such a system in an operational environment.

The results of the basic YF-12 flight research program are being used in the cooperative control program. The pertinent elements of the basic program include investigations of the effect of airframe/propulsion system interactions on flightpath control, measurement of high-speed propulsion system performance, and comparisons of flight test, wind tunnel, and simulator results. Specifically, wind tunnel tests to determine steady-state and dynamic characteristics and to evaluate new inlet control concepts have been made at Lewis Research Center on a full-scale YF-12 inlet. Wind tunnel testing of a 1/3-scale inlet has been conducted by Lockheed Advanced Development Projects at NASA Ames Research Center to investigate scale effects. Tests have also been made at Ames on a 1/12-scale model to measure forces and moments induced by inlet airflow. Several studies have been conducted by Honeywell Inc. and Pratt & Whitney to update existing control systems and explore new control concepts.

The cooperative control program itself consists of two phases. The first phase is concerned with longitudinal flightpath control, that is, altitude and Mach excursions. The influence of atmospheric disturbances such as temperature and pressure changes and airframe propulsion interactions on longitudinal flightpath control is being studied. Control laws for autopilots and stability augmentation systems that are less sensitive to atmospheric changes are being explored. Both classical and optimal control techniques are being used to define the control laws. A first step toward airframe/propulsion control integration will be taken by implementing an autothrottle. Figure 14 shows the schedule for the cooperative control program. The analytical work in Phase I was completed in January, and an autothrottle is being fabricated. The first flight is planned for early 1975.

Phase II will consider lateral-directional interactions such as reduced Dutch roll damping and unstarts. Advanced propulsion and control integration concepts such as optimum cruise control and unstart control utilizing a digital computer will be investigated.

The analytical portion of Phase II began recently. Flight tests of the more promising concepts are expected to begin in late 1975.

A conceptual diagram of the cooperative control system is shown in figure 15. The digital computer is used to compute, coordinate, and command the functions of the inlet, engine, and airframe in response to inputs such as those shown.

CONCLUDING REMARKS

Airframe/propulsion system interactions have been shown to significantly affect aircraft performance, stability, and control. Changes in drag as large as 25 percent (per engine) of the total drag can be involved. Forces and moments as powerful as those produced by the aerodynamic controls have been observed. If not accounted for, these effects can lead to large performance degradations, large flightpath excursions, and increased pilot workload.

Cooperative or integrated operation of the propulsion and flight controls may provide a solution to these problems. Control integration has the potential to not only eliminate the adverse effects of interactions but to significantly improve performance through synergistic effects such as less airframe weight, improved flightpath control, less overall system complexity, and more efficient operating limits. Analytical and flight research programs are underway at the NASA Flight Research Center to investigate the benefits of such a system in an operational environment.

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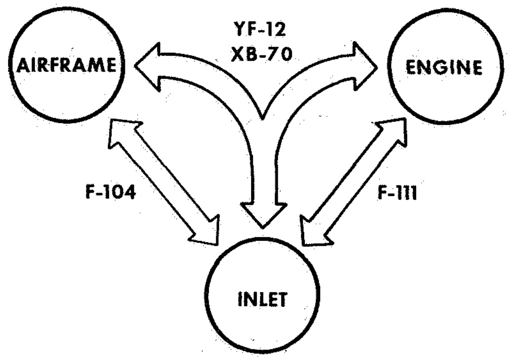


Figure 1. Functional nature of interactions.

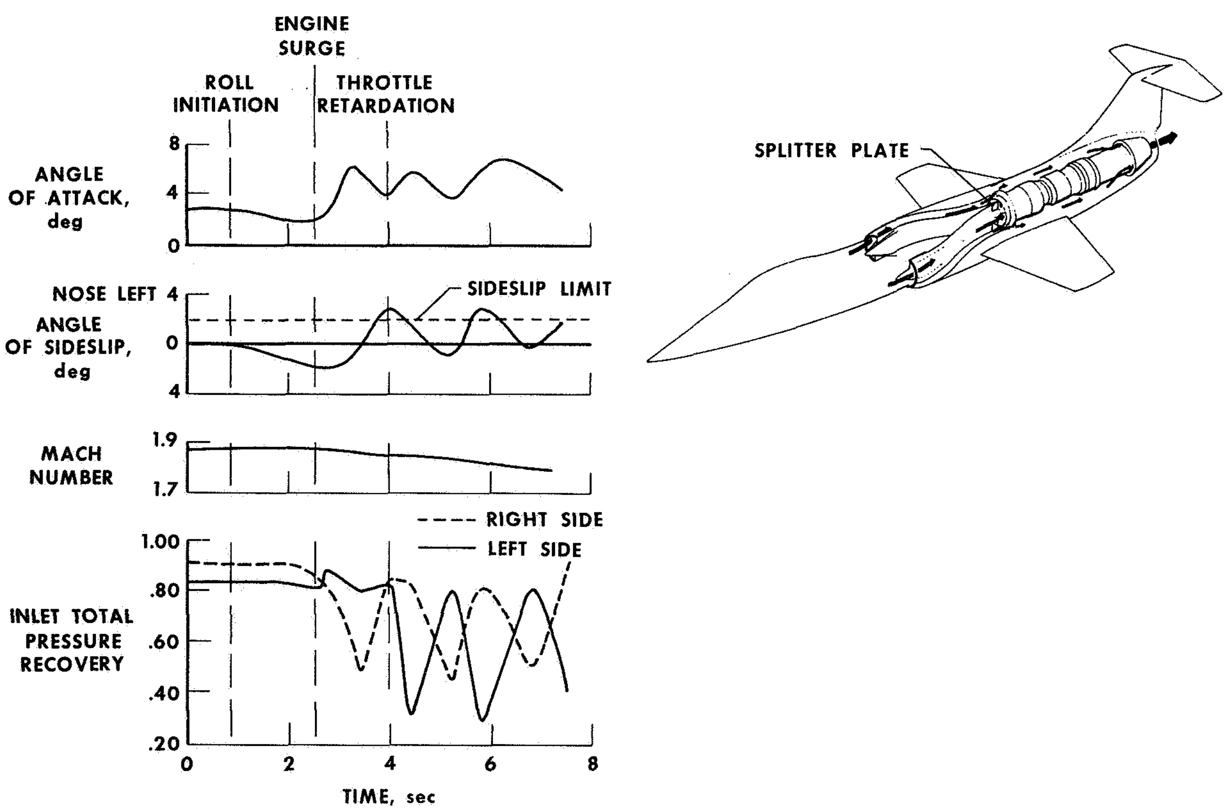


Figure 2. F-104 airframe/inlet interaction. Yaw damper off.

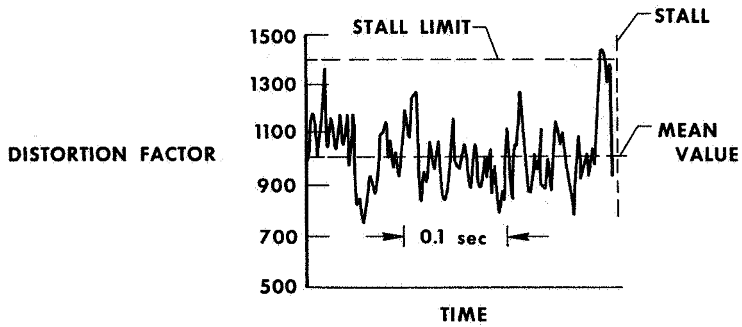


Figure 3. F-111 engine/inlet interaction. Mach 2.17.

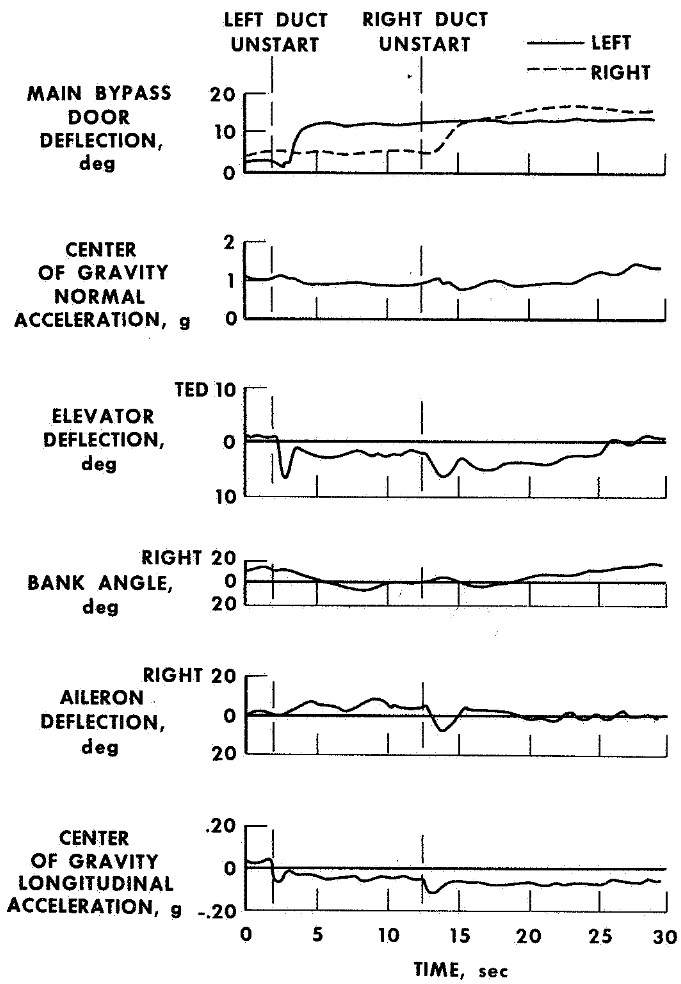


Figure 4. XB-70 engine/inlet/airframe interaction. Mach 3.

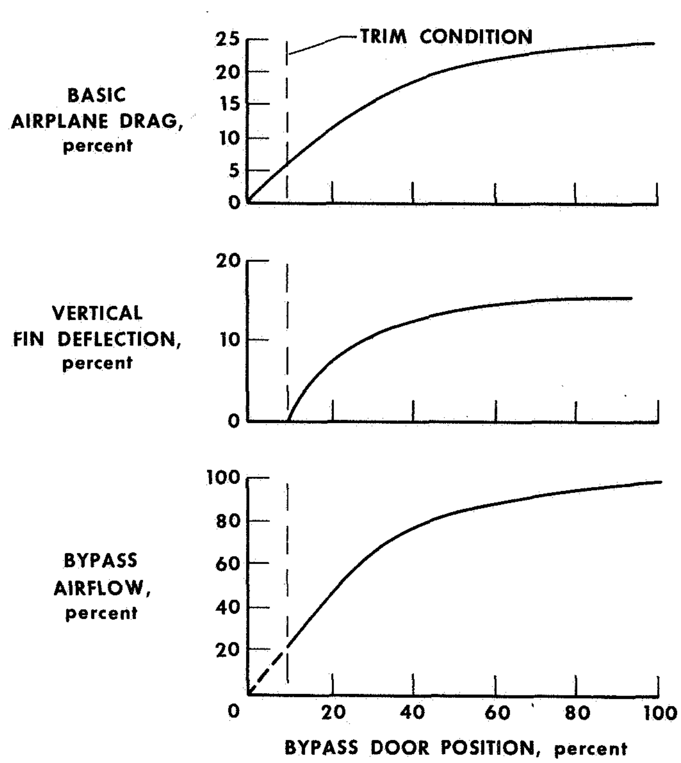


Figure 5. Effect of asymmetric bypass door opening on drag and directional control at Mach 3.

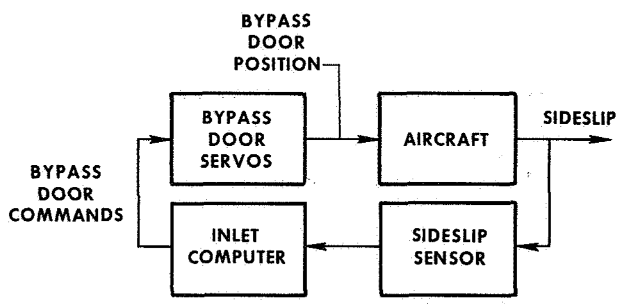


Figure 6. Sideslip coupling due to automatic inlet operation.

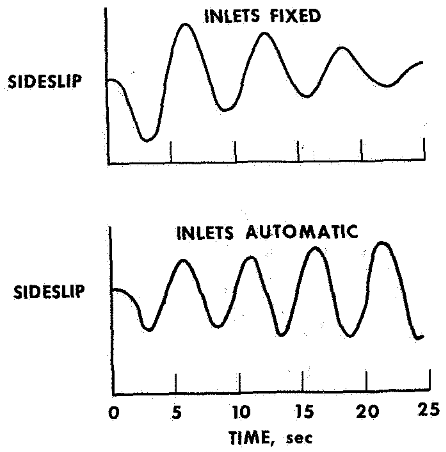


Figure 7. SAS-off rudder pulse response.

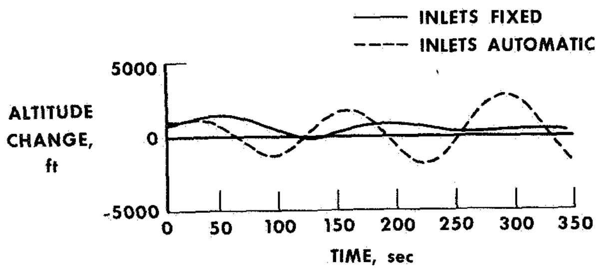


Figure 8. YF-12 controls-free altitude response to a drag pulse.

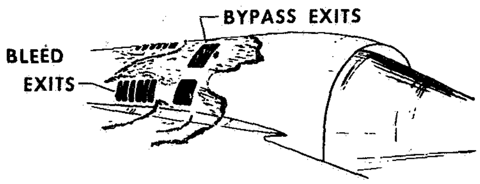


Figure 9. Wind tunnel surface oil flow study. Supersonic cruise Mach number; forward bypass and bleed open.

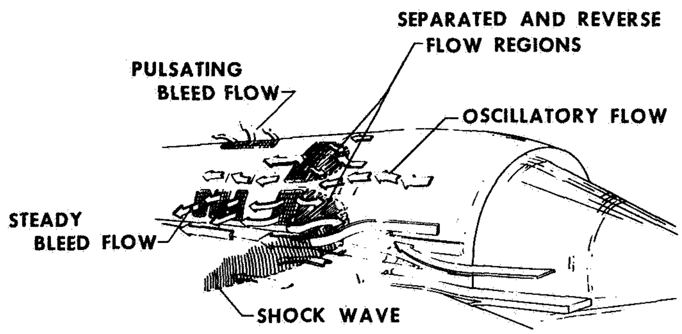


Figure 10. Flight tuft study. Supersonic cruise Mach number; forward bypass doors and bleed open.

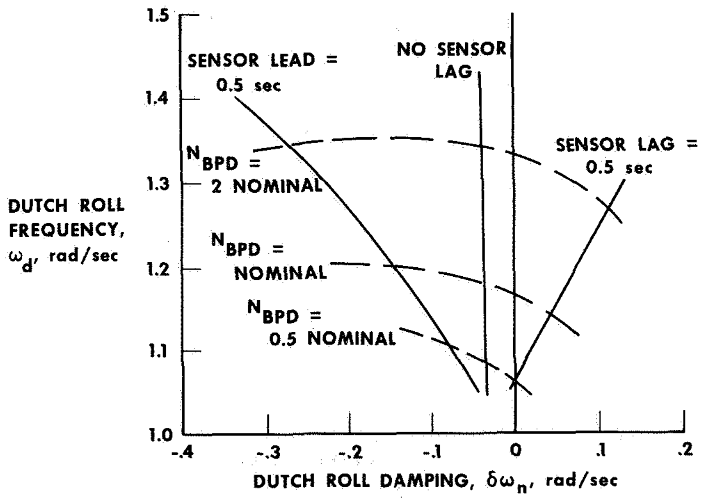


Figure 11. Effect of sideslip sensor lag and bypass door yawing moment on Dutch roll frequency and damping. Automatic inlet operation.

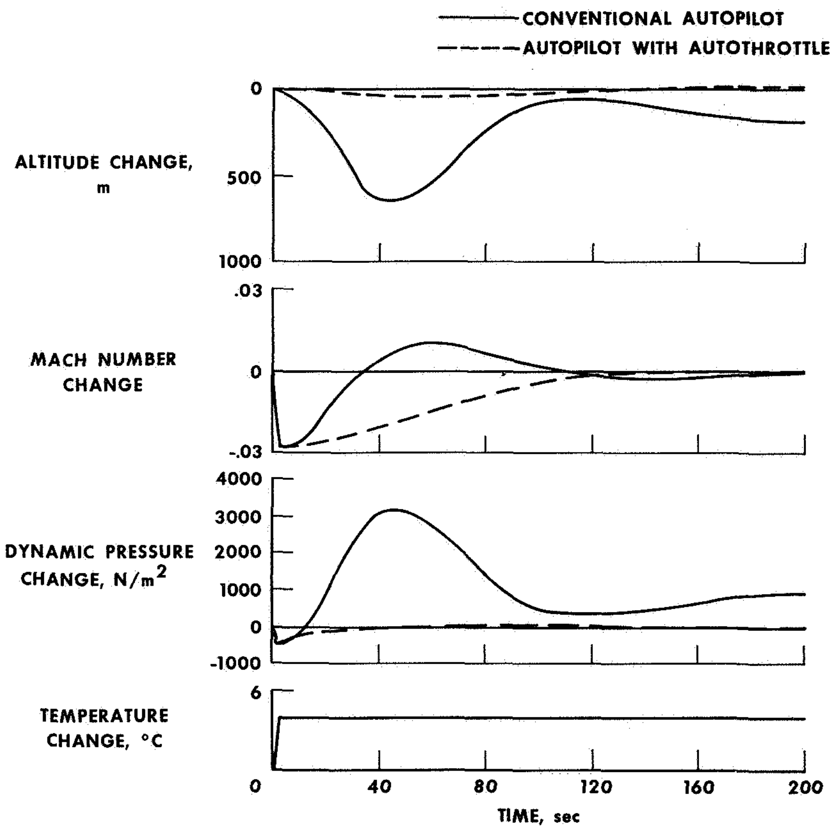
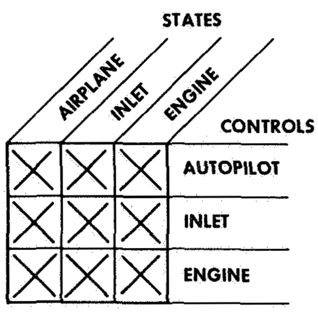
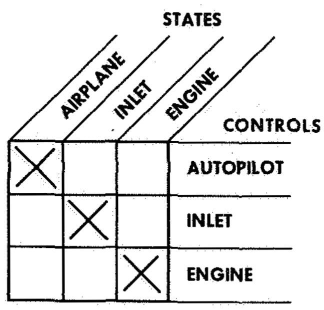


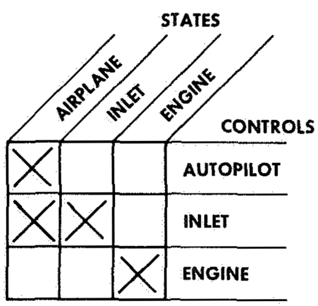
Figure 12. Mach hold autopilot response. YF-12 simulator; Mach 3.



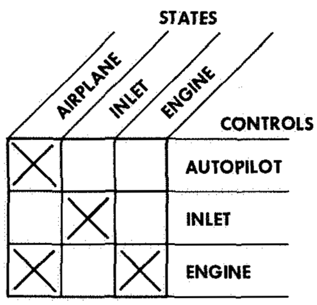
(a) Fully integrated.



(b) No integration.



(c) Partial integration (airplane-inlet).



(d) Partial integration (autothrottle).

Figure 13. Options for control integration.

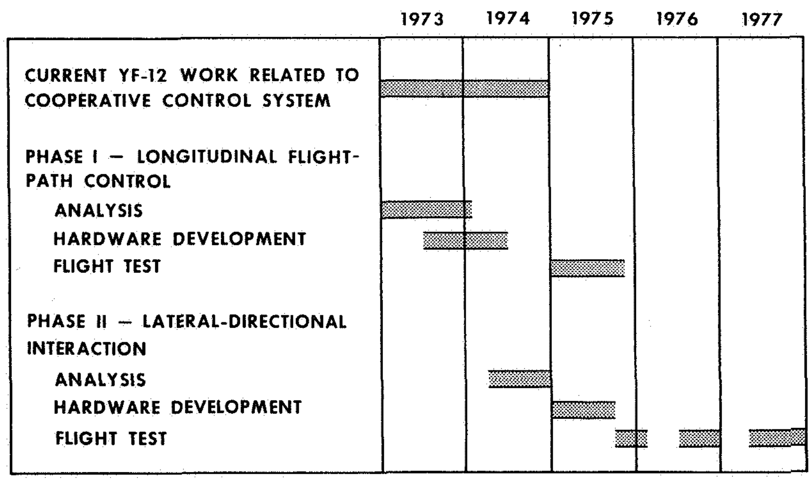


Figure 14. YF-12 cooperative control system schedule.

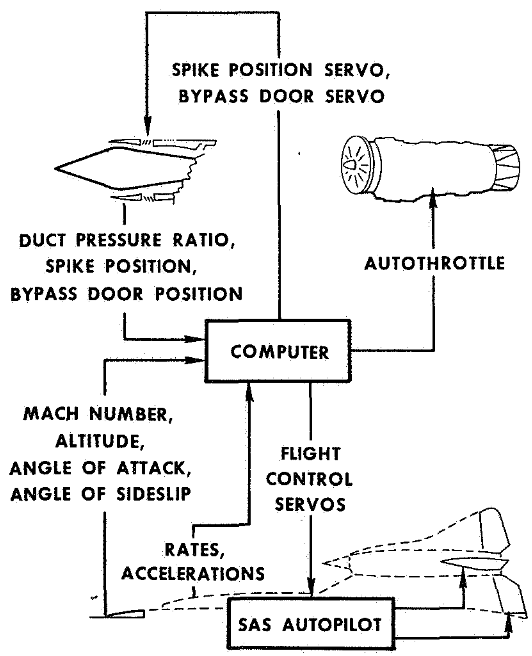


Figure 15. Cooperative autopilot/SAS/propulsion control system.