Lift-Engine Inlet Performance and Operation," *Journal of Aircraft*, Vol. 4, No. 2, March-April 1967, pp. 125–132.

[6] Kirk, J. V. and Barrack, J. P., "Reingestion Characteristics and Inlet Flow Distortion of V/STOL Lift Engine Fighter Configurations," *Journal of Aircraft*, Vol. 6, No. 2, March–April 1969, pp. 116–122.

[7] Shumpert, P. K., Harris, A. E., and Picklesimer, E. A., "XV-4B Inlet Development Test Report," ER-9243, July 1967, Lockheed-Georgia Co., Marietta, Ga.

[8] Blackaby, J. R. and Watson, E. C., "An Experimental Investigation at Low Speeds of the Effects of Lip Shape on the Drag and Pressure Recovery of a Nose Inlet in a Body of Revolution," TN 3170, April 1954, NACA.

[9] "Propulsion/Performance/Stability and Control," *VTOL Integrated Handling Qualities Investigation Vehicle*, ETP 623, Vol. III, July 1965, Lockheed-Georgia Co., Marietta, Ga.

[10] Shumpert, P. K. and Harris, A. E., "Full-Scale V/STOL Lift Engine Inlet Development Tests," ER-9663, Vol. I–III, April 1968, Lockheed-Georgia Co., Marietta, Ga.

JULY-AUG. 1969 J. AIRCRAFT VOL. 6, NO. 4

A Control System Concept for an Axisymmetric Supersonic Inlet

K. S. Chun* and R. H. Burr†
The Boeing Company, Seattle, Wash.

A control system concept for the operation of an axisymmetric supersonic inlet in a mixed compression mode is described, and the test results to substantiate the soundness of the concept are presented. The control system consisted of a centerbody control loop, a normal shock control loop, and a restart control loop. The analytical considerations and wind-tunnel test data leading to the selection of the control pressure signals required for the system are discussed. The control loop tests were conducted at a number of selected Mach numbers from 2.0 to 2.6 on two 11.24-in.-lip variable-geometry inlets. All control loop components, except the close-coupled pressure transducers, the hydraulic servovalves, and the actuators, were simulated on an analog computer. Control loop responses were evaluated as the Mach number, the inlet angle of attack, and the downstream airflow were varied in both ramp and sinusoidal forms. The inlet restart control function was also evaluated. The test results indicated that the control system concept, with the selected control signals, satisfactorily meets the control requirements of the mixed compression mode.

Nomenclature

Ap	= exit plug area
E_B	= integrator limit
E_{CB}, E_{NS}	= error signals
$G_{CB}(s), G_{NS}(s), G_{SB}(s)$	= pneumatic line dynamics
K_{BY}, K_{CB}	= loop gains
M_L	= Mach number ahead of inlet
M_{TH}	= inlet throat Mach number
P_C	= restart control pressure
P_{CB}	= centerbody control pressure, cowl static
P_{CBM}	= centerbody control pressure, manifolded cowl static
P_{CS}	= cowl static pressure
P_{TL}	= tunnel total pressure
P_{NS}	= normal shock control pressure
P_{SB}	= shock-bias control pressure
P_{TNS}	= throat total pressure
P_{T2}	= compressor face total pressure
PR	= control pressure ratio
R_{CB}	= centerbody radius
s	= Laplace operator
T_{CB}, T_{NS}	= time constants
α	= inlet angle of attack
θ	= circumferential angle

Presented as Paper 68-581 at the AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio, June 10–14, 1968; submitted August 5, 1968; revision received April 11, 1969.

* Senior Group Engineer, Inlet Controls, Propulsion Staff, Supersonic Transport Branch.

† Research Engineer, Propulsion Staff, Supersonic Transport Branch. Member AIAA.

Introduction

SUPERSONIC aircraft with a high Mach number cruise condition must employ variable-geometry inlets with an efficient control system to achieve high performance and stable airflow for the engine. Rapid geometry changes for stable operation during environmental turbulence, engine transients, and airplane maneuver are among the most critical requirements for the inlet control system.

This requirement is quite severe for mixed compression inlets because the shock system is sensitive to many variables. Therefore, a major effort must be made to develop a control system that will sense these variables and provide fast response. This paper presents a control system concept found to be satisfactory for the operation of an axisymmetric

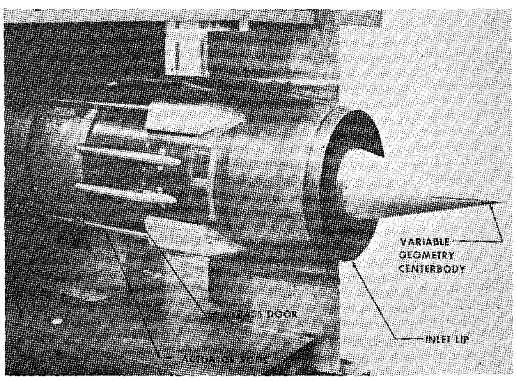

Fig. 1 11.24-in. variable-geometry inlet model.

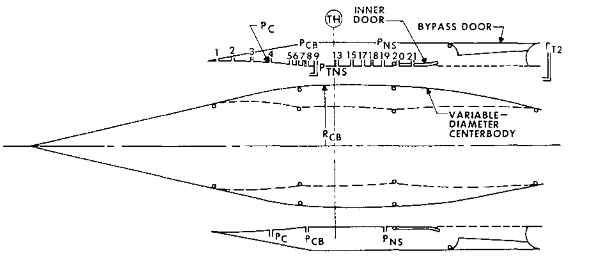

Fig. 2 Inlet model control pressure tap and probe locations.

supersonic inlet operating in the mixed compression mode. Also presented are the wind-tunnel test data used to select pressure signals for the control system.

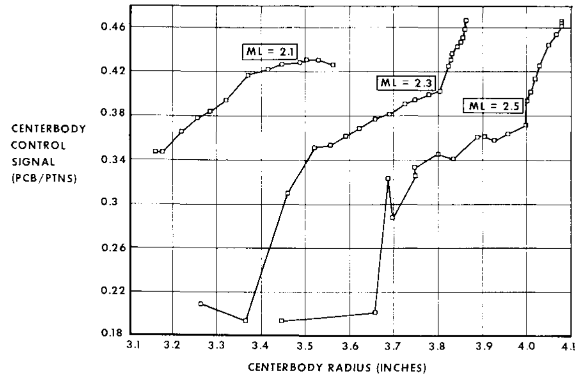

Fig. 4 Centerbody control signal.

Description of Model and Facilities

Control pressure signals were investigated with several small-scale axisymmetric inlet models. The most significant control signal tests and control loop response tests were conducted with two 11.24-in.-lip-diam inlets, one of which is shown in Fig. 1. Both of these models were equipped with a variable-diameter centerbody, the first being fitted with a solid cowl and the second with a variable-bypass door cowl. A schematic of the inlet model is presented in Fig. 2. The inlet models were installed with the necessary boundary-layer bleed holes for high performance. Strain gage pressure transducers with short pneumatic lines were used to convert selected pneumatic control signals to electrical signals.

Mach number changes were generated by rapidly varying the wind-tunnel nozzle; inlet angle of attack changes were generated by tilting the tunnel test-and-discharge section; and the simulation of engine airflow changes was effected by operating the model exit plug. The ramp and sinusoidal changes of these variables were imposed by preprogramming desired functional features in an input signal generator.

Control Pressure Signal Tests

The performance of the inlet control system depends largely upon the pressure signal characteristics. It is important, therefore, that careful studies be carried out in determining the pressure signals to be used in the control system. Preliminary control signal tests were conducted with various small-scale axisymmetric models with lip diameters ranging from 2.85 to 5.6 in. Some of these models had sets of solid interchangeable centerbodies designed to simulate variable centerbody inlets operating over a range of Mach numbers. Data from these tests were used to map the trends of pressure variations and to make a preliminary selection of control pressure signals.

There are various ways of sensing the inlet and airplane operating conditions for achieving the required control function. For the present inlet control system, signals were sought which could utilize constant reference signals for each control loop. The generation of control reference signals, as functions of other variables, would add to the complexity of the inlet control system and, therefore, lower the reliability and the accuracy of the system. A further reduction in system complexity can be achieved if the control signals directly sense the outputs of controlled variables.

A search for control signals with these features led to the selection of a static-to-total pressure ratio just forward of the throat station for the throat area control. A ratio of static pressure downstream of the normal shock to the throat total pressure was selected for the normal shock control. The throat static-to-total pressure ratio, will, theoretically, be a constant value for a set throat Mach number, therefore meeting both previously mentioned objectives. The pressure ratio for normal shock control should also be nearly constant at on-design conditions, since normal shock strength will be constant and airflow diffusion from the throat station to the control signal tap will vary only slightly for the variable-diameter centerbody inlet. Test results, in general, confirmed these trends, as can be seen in the data presented.

The desired centerbody (throat area) control signal should be located close to the throat, but must not be affected by the presence of the normal shock. The normal shock causes changes in the boundary layer, which in turn affects the control signals. Figure 3 shows a plot of the normal shock boundary-layer effects. As the shock moved forward, those taps close to the throat showed a sudden rise. Those farther forward of the throat showed little or no effect from the normal shock boundary layer; however, the possibility of using a constant control reference signal is reduced with these pressures. Compromising the two contradicting trends, the cowl static tap P_{CS7} was selected as the centerbody control signal P_{CB}.

Figure 4 shows the selected centerbody control signal P_{CS7} variation with the centerbody radius. The plot reveals large slope changes in the curves, which predict undesirable

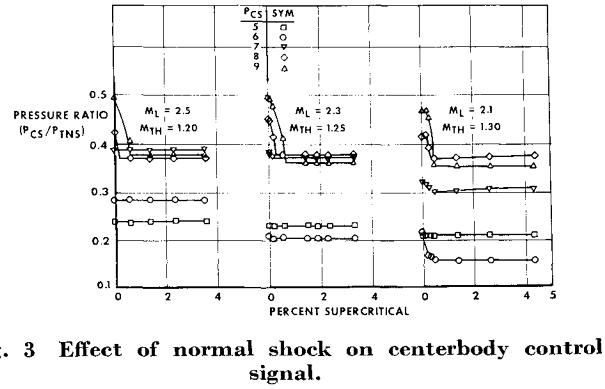

Fig. 3 Effect of normal shock on centerbody control signal.

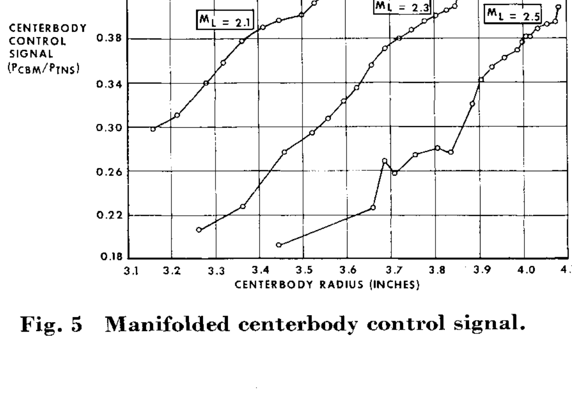

Fig. 5 Manifolded centerbody control signal.

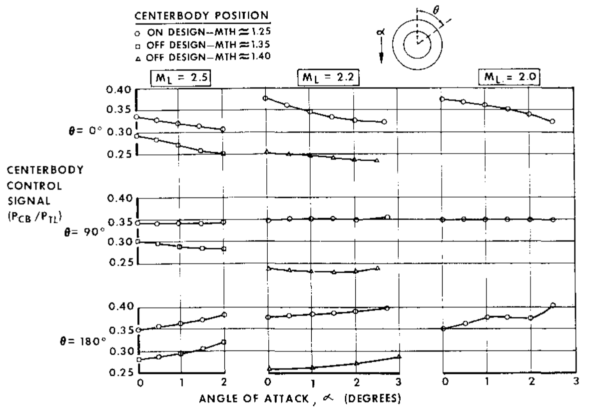

Fig. 6 Angle of attack control signal.

gain changes in the signal. Use of a midstream static tap at the same station, in an attempt to eliminate the suspected boundary-layer effect, produced a similar trend. On close examination, it was found that a reflected oblique shock of the cowl lip shock crossing the tap was the cause of these slope changes.

In order to find a way to smooth out the gain variations, signals from three probes were averaged, and a plot was made. The result, shown in Fig. 5, indicates a considerable improvement in the signal characteristics. The same effect may be achieved by simply manifolding several static pressure taps together.

An important function of the centerbody control loop was to maintain a throat Mach number which would provide a margin so that sudden reduction in freestream Mach number would not cause frequent inlet unstarts. A reasonable compromise between maximum pressure recovery and freedom from inadvertent intake unstarts due to upstream disturbances led to the selection of the throat Mach number of 1.25 for this study. Tests showed that the centerbody control signal set at 0.39, corresponding to a throat Mach number of 1.25, provided a freestream Mach number tolerance of approximately 0.05 for inlet unstart throughout the Mach number range from 1.8 to 2.7.

When the inlet operates at some angle of incidence to the flow, the throat Mach number will not be uniform. This can be seen in Fig. 6, where the 180° tap indicates a lower Mach number, and the 0° tap indicates an increased Mach number. To prevent the upstream Mach number tolerance from being significantly reduced due to the lower throat Mach number, it is apparent that more than one throat Mach static tap will have to be used. It was decided, therefore, to use four taps spaced around the throat annulus and to select the tap that reads the highest static pressure. This will result in an increase in average throat Mach number during an angle of attack operation; however, the stability margin against upstream disturbances will remain essentially unchanged.

The variation of throat total pressure as a function of inlet angle of attack was insignificant. It was found that the use

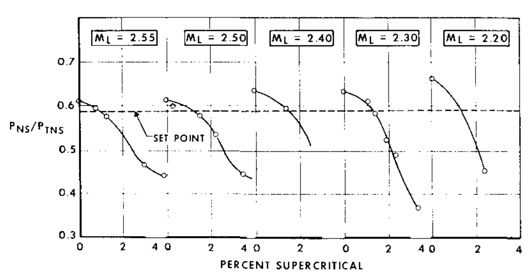

Fig. 7 Normal shock control signal.

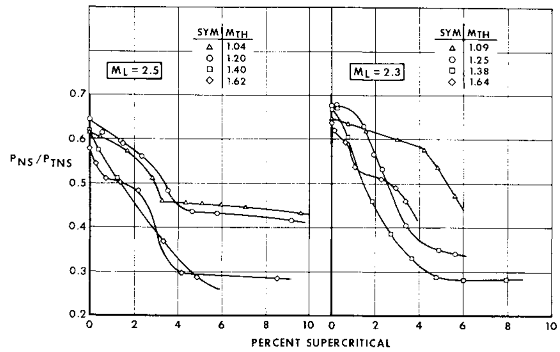

Fig. 8 Effect of throat Mach number on normal shock control signal.

of two total probes, 90° apart, would generate a constant pressure level for an angle of attack of up to 3°.

Static pressure taps located at various stations downstream of the throat were investigated for the normal shock control signal. A set of manifolded statics was also investigated. Selecting P_{CS19} as the control signal P_{NS} and testing it over a range of Mach numbers gave the results shown in Fig. 7. These data indicate that a constant set point pressure ratio would give a fairly uniform gain and supercritical margin (critical pressure recovery minus operating pressure recovery). Figure 8 shows how the signal is affected when the centerbody position is off-design, causing throat Mach number changes. These conditions may occur during inlet transients or inlet centerbody control failures. It can be seen that if a constant set point ratio is maintained, the bypass loop will cause the normal shock to move to the throat and unstart the inlet if the throat Mach number is appreciably larger than the design value. This must be prevented by modifying the normal shock control signal pressure ratio set point. In the present control system concept, this is accomplished by "cross-coupling," i.e., biasing the set point ratio as a function of the centerbody control loop pressure signal P_{CB}/P_{TNS}.

It is necessary that a signal be provided which will indicate at all times whether the inlet is started or not. This is required to initiate an inlet restart, if an inadvertent unstart should occur, and to provide the flight engineer with an indication of the inlet operating condition. Analytical considerations indicated that a cowl static, located between the lip and throat, should give a clear start-unstart signal. Based on data obtained from numerous test conditions with both unstarted and started inlets, a cowl static tap P_C upstream of the throat, shown in Fig. 2, was selected for the purpose. The characteristics of this pressure signal at different test conditions, as normalized by the throat total pressure, is presented in Fig. 9. The control pressure signals thus selected for the control system tested in this study are shown in Fig. 2.

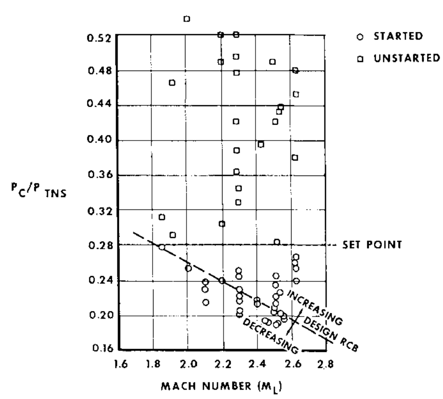

Fig. 9 Restart control signal.

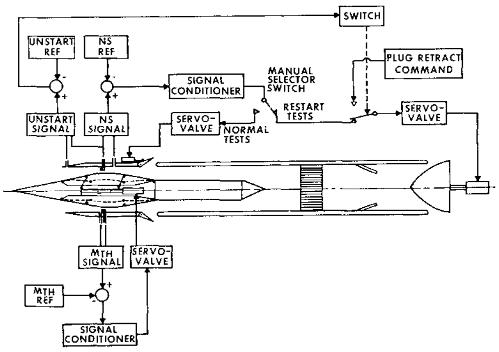

Fig. 10 Inlet control loop test arrangement.

Control Loop Tests

Wind-tunnel tests were conducted on two 11.24-in.-inlet models to examine the suitability of the selected control pressure signals and to verify the control loop design concept. A schematic of the control loop test arrangement is presented in Fig. 10. In addition to the usual instrumentation to measure airflows and inlet performance, the inlet was equipped with strain gage pressure transducers for the control signals and also hydraulic servovalves and actuators for the centerbody, bypass doors, and the exit plug.

The basic control loops investigated can be identified in Fig. 10. They are the centerbody loop, the bypass door loop, and the restart control loop. More detailed information on the control loops tested is given in Fig. 11. The components simulated on the analog computer were dividers, comparators, pneumatic line dynamics, pressure ratio sensor dynamics, and variable gains. Necessary electrical signal conditioners were employed as required. In addition to the basic control loops, a shock-bias loop and a cross-coupling loop shown in the figure were investigated. The bypass door control signal P_{NS} was generated by manifolding the four taps located at the same inlet station. The centerbody control signal P_{CB} was generated by selecting the larger of the two signals obtained from the two taps located at the same inlet station, 180° apart.

Tests were carried out by varying the transfer function gains and coefficients, with and without cross-coupling or shock bias. Important findings of the control tests are presented in the following sections.

Independent Loop Response Tests

Prior to testing the other control loop response, small-size step-error signals were imposed at the comparators, and the centerbody and bypass door closed loop responses were examined. The test data set forth the approximate ranges of gain variation that could be used in the control loops.

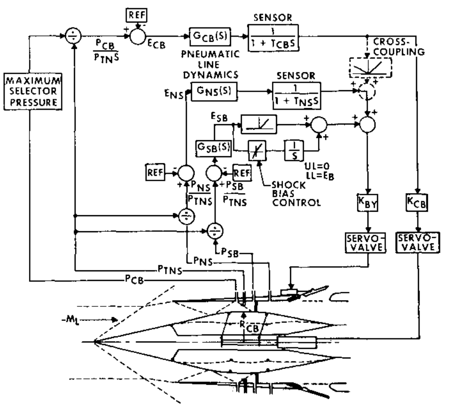

Fig. 11 Inlet control loop block diagram.

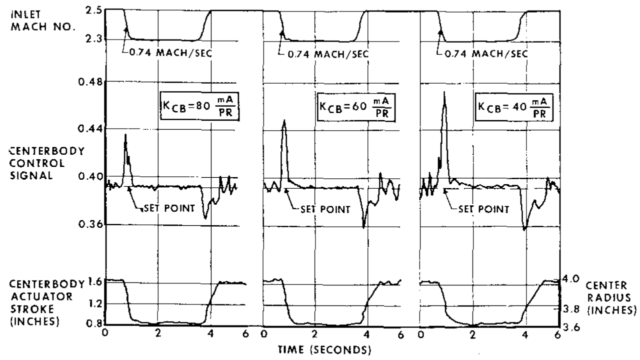

Fig. 12 Centerbody response to ramp Mach changes.

An example of centerbody loop response tests recorded during the inlet Mach number changes is shown in Fig. 12. Possible interference of the bypass door loop with the centerbody loop was avoided by running with either the bypass door loop turned off or the inlet normal shock positioned initially far downstream of the inlet throat. Figure 12 shows the effects of gain increase to the centerbody actuation. The centerbody radius plots reveal a nonlinearity between the radius increasing and decreasing directions. The centerbody loop was also subjected to inlet Mach number sinusoids with frequencies up to 5 Hz.

Two examples of the centerbody loop responses to the inlet angle of attack changes are shown in Figs. 13 and 14. Figure 13 shows the loop response to unidirectional angle of attack changes of approximately 2.7° with a 2.9°/sec rate. As the angle of attack increased, the leeward side P_{CB} increased sensing the decrease in throat Mach number, and the control reduced the radius to maintain a throat Mach number of 1.25 at that section of the throat annulus. Without the control loop action, the inlet would have unstarted at an angle of attack of about 2.5°. Response to a 0.25-Hz angle of attack sinusoid is shown in Fig. 14. It can be seen that as the angle of attack alternated between the positive and negative directions, the larger of the two control signals located 180° apart was selected to control the centerbody. Thus, the centerbody radius is reduced to smaller values for approximately every half-cycle of the angle of attack sinusoid, during which time the angle of attack is other than zero. The control signal is in phase with the input, while the centerbody radius lags the input by approximately 21°.

The bypass door control loop was tested while imposing downstream airflow ramps with and without the shock-bias control loop. For this portion of tests, the centerbody control loop was left operating, since it showed little or no interference with the bypass door loop.

The primary objective of the shock-bias loop was to physically locate the normal shock at the desired position in the inlet throat section. To achieve this, the control signal measured by the taps located immediately upstream of the desired normal shock position and an integrator with

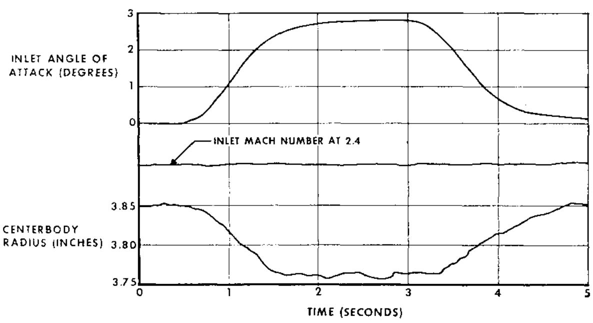

Fig. 13 Centerbody response to ramp angle of attack change.

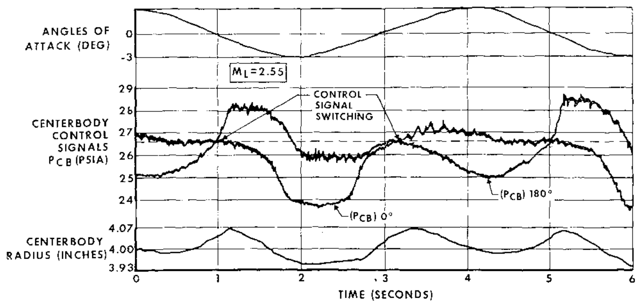

Fig. 14 Centerbody loop response to sinusoidal angle of attack change.

adequate gains were used, as can be seen in Fig. 11. Since the shock-bias control signal would show a steep pressure rise as the normal shock traverses the taps in an upstream direction and vice versa, it should be possible to locate the normal shock at the tap station if the integrator were used with a reference signal having a value reasonably close to the midpoint of the pressure change. When this is done, it is possible to achieve two important features: 1) elimination of the differences in the normal shock operating position caused by inlet-to-inlet size variations and by engine-to-engine airflow variations and 2) relaxation of the control accuracy required on the bypass door loop, particularly of the accuracy requirement on the P_{NS}/P_{TNS} pressure ratio sensor, which is the predominant source of control inaccuracy.

To extend the use of the shock-bias loop, a unilateral gain shown in Fig. 11 was added later. Its purpose was to quickly apply a rapid restoring action to the normal shock when it moves upstream of the desired normal shock operating position.

During the series of tests, the feasibility of physically locating the normal shock at the shock-bias control signal tap station was demonstrated. When the shock-bias loop was activated, the normal shock position stabilized at the P_{SB} station, regardless of the variation applied to the reference signal in the bypass door control loop. The shock-bias loop also was found effective in attenuating the transient upstream movement of the normal shock. This can be seen by the positive excursion of the normal shock signal in Fig. 15.

Combined Loop Tests

Combined centerbody and bypass door control loop tests were conducted with the shock bias operating, with the cross-coupling operating, or with neither of these loops operating. Imposed disturbances were Mach number ramp changes. The effect of shock-bias loop in reducing the upstream normal shock translation was evident from the tracing of the normal shock control signal. It is attributed to the larger gain introduced by the shock-bias loop.

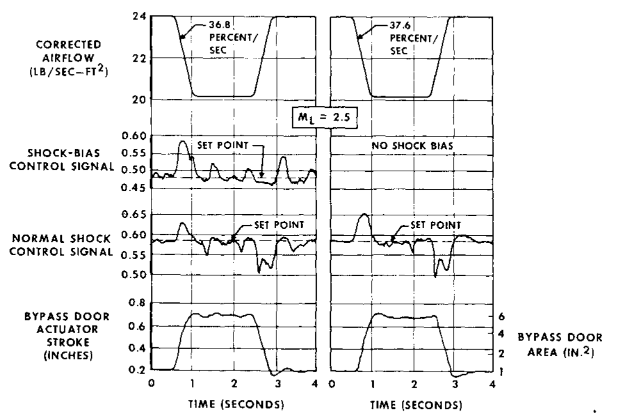

Fig. 15 Effect of shock bias on bypass door loop response.

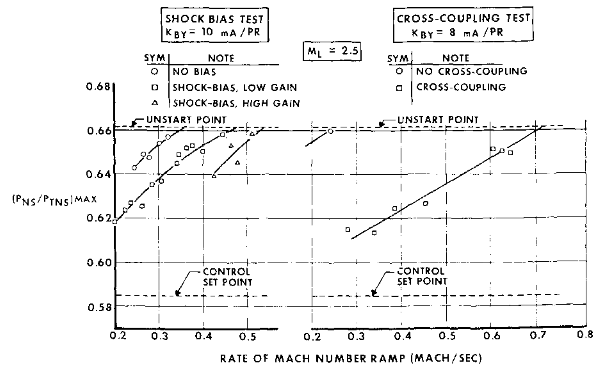

Fig. 16 Effect of shock bias and cross-coupling.

The cross-coupling loop was to alleviate the problem arising from shifting of bypass control pressure signal curves during extreme off-design centerbody conditions (see Fig. 8). The cross-coupling signal added to the bypass door loop was generated as a function of centerbody control signal E_{CB}, as shown in Fig. 11. Cross-coupling markedly increased the bypass door opening rate and restrained the upstream normal shock translation to a very small amount. Curves summarizing the effect of shock bias and cross-coupling are presented in Fig. 16. It is shown that the maximum Mach number ramp that can be imposed is much larger with the shock bias or cross-coupling.

Restart Control

The restart control was tested by two different methods. In this series of tests, due to the limitation of bypass door discharge capacity, the exit plug was used in place of the bypass doors (see Fig. 10). The first restart method, which is the normal restart scheme, was to detect the unstarted inlet condition by the restart signal $P_C/_{TNS}$ and then to switch on the preset plug retract command signal in the plug control loop. No special signal switching was necessary for the centerbody loop since aerodynamic changes automatically generated a collapse signal to the centerbody control loop for an unstarted inlet and vice versa.

After establishing a steady-state operating condition with the automatic controls on, the inlet was unstarted by momentarily closing the plug through a preset position command signal. As soon as the inlet was unstarted, the close signal was disconnected, and the automatic controls were allowed to restore the steady-state inlet operation. One example of such a restart transient is shown in Fig. 17. When the restart control signal exceeds the set point indicating an inlet unstart, the plug is commanded to open and reaches the preset position in a short time. The normal plug (bypass) control signal is

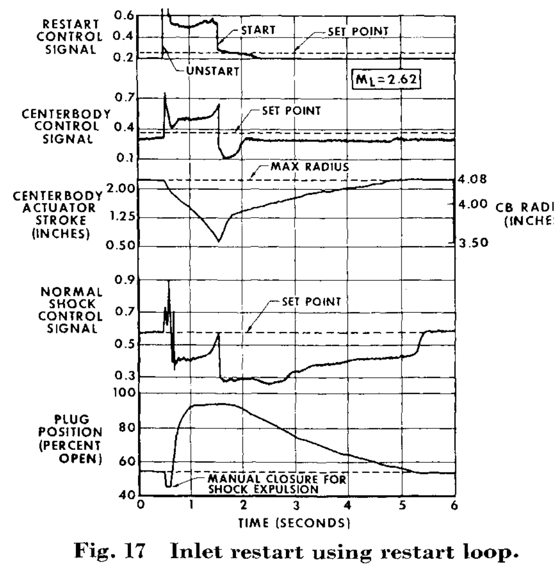

Fig. 17 Inlet restart using restart loop.

disconnected because it would close the plug rather than open it. During this time, the centerbody signal detects the inlet unstart by sensing the subsonic flow within the inlet and commands the centerbody to contract for larger throat area. When the throat area increases sufficiently, the inlet shock system is reswallowed. The instant the terminal normal shock passes downstream traversing the restart sensor tap, normal control action is restored. The centerbody control signal now expands the centerbody, and the normal shock control signal closes the plug, nulling the error signals. The tracings show that the centerbody radius is restored in about 2.2 sec and the plug is restored in about 4 sec after the inlet restart. The reason that the centerbody control signal was not on the set point was because the centerbody radius actuation linkage bottomed out in the expanding direction. Further tests with added instrumentation are required to examine the transient inlet performance during the restart; however, the tests results indicate that the restart concept is acceptable.

To explore the possibility of eliminating the restart sensor circuit and the associated switching, a restart that uses the cross-coupling, instead of the restart sensor circuit, was investigated. The difference in this method is that a correct error signal was generated for the plug (bypass) control loop by using a function of the centerbody control error signal E_{CB} during the period of time that the inlet was in an unstarted mode. The centerbody control mode was the same as in the first method. Effective restarts were demonstrated at Mach 2.62 using this method. Difficulty, however, is expected with this method in that it may require different cross-coupling functions for different Mach numbers.

Conclusions

Feasibility of the inlet control system design for the mixed compression mode of the axisymmetric variable-diameter centerbody inlet was demonstrated by the various dynamic tests. The centerbody and normal shock control loops, with aerodynamic feedback and constant reference signals, functioned properly against anticipated upstream and downstream disturbances. Test data also verified the benefit of using the shock-bias and cross-coupling loops. Use of throat Mach number to control the centerbody radius was proved to be effective for angle of attack and upstream Mach number disturbances. Both of the inlet restart control methods tried were found to function well, although further tests with dynamic inlet performance measurements are desired.

Selection and mapping of control pressure signal characteristics constitute a large part of the inlet control system development program; therefore, considerable time and effort should be provided for this work. The selected control signals functioned satisfactorily for the control loops tested.