RESTART AND HIGH RESPONSE TERMINAL SHOCK CONTROL FOR AN AXISYMMETRIC MIXED-COMPRESSION INLET WITH 60-PERCENT INTERNAL CONTRACTION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

Results from investigations of normal shock and restart control systems are presented. Included are analysis followed by experimental results obtained from an axisymmetric, mixed-compression inlet tested at Mach 2.5. The inlet was terminated successively with a large volume, a choked orifice at the engine face station, and a turbojet engine. The normal shock control systems were subjected to downstream (0 to 140 Hz) and upstream (0 to 20 Hz) flow disturbances. The normal shock controllers investigated indicated increased performance with electronic compensation and multiple feedback. The restart controllers maintained closed-loop bypass door control throughout the restart cycle, minimizing distortion while maximizing pressure recovery.

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SUMMARY

Results from investigation of normal shock and restart control systems utilizing
100 hertz bypass doors and 250 hertz pressure transducers are presented. Included are
analyses methods followed by experimental results obtained from an axisymmetric,
mixed-compression, translating-centerbody inlet tested at a Mach number of 2.5 in a
10- by 10-foot wind tunnel. The normal shock control systems were subjected to down-
stream and upstream flow disturbances from 0 to 140 hertz and 0 to 20 hertz, respec-
tively. Large amplitude transients were also investigated. The inlet was terminated
alternately with a large volume, a choked orifice at the engine face station, and a J-85-13
turbojet engine. The normal shock controllers investigated indicated increased per-
formance with electronic compensation and use of multiple feedback. Restart controllers
were investigated for the inlet terminated with the large volume. Closed-loop bypass
door control was maintained throughout the restart cycle which minimized distortion and
total pressure variations at the engine face station.

INTRODUCTION

To achieve maximum efficiency in a started mixed-compression inlet, it is desirable
to maintain the terminal shock as near the throat as possible. Since downstream and up-
stream disturbances can displace the shock and cause inlet unstart, it is necessary to
regulate shock position with active control. Such a control system consists of overboard
bypass doors, located near the engine face, operating in a closed loop based on aerody-
namic signals. In the case of the restart control, manipulation of the contraction ratio
by means of a collapsing or translating centerbody is also required.

The performance of present inlet control systems is limited primarily by the dynamics of the bypass doors and aerodynamic sensors. This paper presents the results of an investigation of inlet control systems which utilize high-performance bypass doors and aerodynamic sensors. The purpose of the investigation was to evaluate controls whose performance was dictated primarily by the inherent inlet dynamics, rather than control hardware.

The first part of the investigation was concerned with control of the normal shock in the started inlet. This was followed by a study of restart control systems, utilizing bypass door control systems from the initial investigation.

SYMBOLS

G_c controller transfer function

H_1 throat total pressure, N/m^2

j $\sqrt{-1}$

K_3 minor loop controller gain

P_1 cowl lip static pressure, N/m^2

P_2 throat exit static pressure, N/m^2

P_3 diffuser exit static pressure, N/m^2

S Laplace transform variable

W_d downstream disturbance air flow, kg/sec

W_u upstream disturbance air flow, kg/sec

X_{CB} centerbody position, m

X_s normal shock position, m

Δ denotes incremental change in variable

ω frequency, rad/sec

APPARATUS AND PROCEDURE

The inlet selected for this investigation was an axisymmetric, mixed-compression model with a cowl-lip diameter of 0.465 meter. The design Mach number was 2.5 with 60 percent of the supersonic area contraction occurring internally. The steady-state performance and dynamics of this inlet are presented in references 1 and 2, respectively.
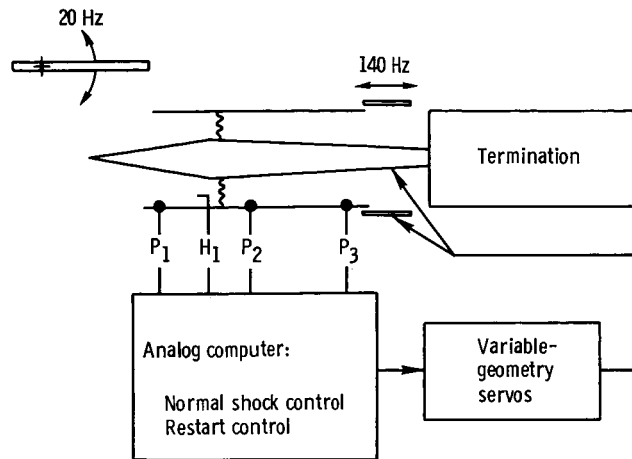
Figure 1. - Inlet control experiment.

A schematic representation of the inlet as it was installed in the Lewis 10- by 10-Foot Supersonic Wind Tunnel is shown in figure 1. Variable contraction ratio was achieved with a translating centerbody actuated by an electrohydraulic servomechanism. Six sliding plate overboard bypass doors were located symmetrically around the inlet at the diffuser exit. Each door was independently controllable by means of individual electrohydraulic servomechanisms. The bypass door servos were designed to operate sinusoidally to 140 hertz. They exhibited flat response to 100 hertz at an amplitude which produced a disturbance equivalent to 6 percent of matched engine airflow (see fig. 2).
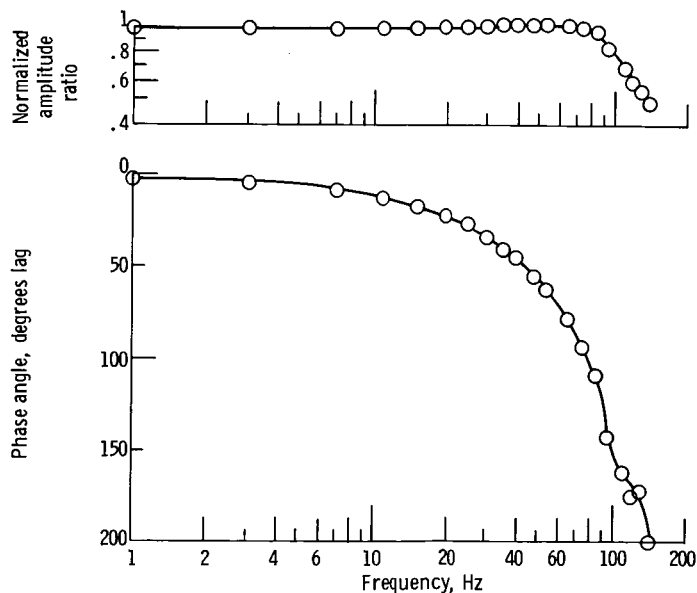

Figure 2. - Bypass door frequency response.

Close-coupled dynamic pressure transducers were utilized for data and control. Their frequency response was flat to within +3 decibels to approximately 250 hertz. Those signals used for control are indicated on figure 1. They include statics at the cowl lip (P_1), throat exit (P_2), and diffuser exit (P_3), and a total probe at the inlet throat (H_1). Provisions were made to alternately terminate the inlet with a large volume cold pipe, choke plate at the engine face station, and a J-85-13 turbojet engine.

The control systems investigated were implemented by means of an analog computer located in the control room. The computer was used to close the control loops between the feedback signals and the variable geometry servos. The criterion for evaluating the normal shock control systems was the minimization of disturbance induced shock motion. The control system under test utilized three of the overboard bypass doors operating in parallel. The remaining three doors were oscillated sinusoidally to 140 hertz to provide a symmetric downstream flow disturbance. An oscillating plate located upstream of the inlet produced gust-like disturbances to 20 hertz.

The restart controls were evaluated by monitoring internal pressure transients throughout the restart cycle. The criteria were minimization of inlet distortion and maximization of pressure recovery throughout the restart. A pulse-type disturbance from three of the doors produced the inlet unstart.

NORMAL SHOCK CONTROL

The normal shock control systems investigated used the high-performance bypass doors as the manipulated variable. Several controller types were comparatively evaluated to determine the degree of performance obtainable with increased electronic compensation and minor loop feedback.

Analysis and Design

Design of the normal shock controllers was performed prior to the availability of the experimental inlet dynamics. However, an analog computer simulation of inlet dynamics (ref. 2) and the steady-state inlet characteristics (ref. 1) were available.

Figure 3 illustrates the inlet control systems analyses and design procedures. The simplified wave model of inlet dynamics was programmed on the analog computer using Padé networks to simulate the dead times. This yielded the frequency response of shock position and inlet pressures to upstream and downstream flow disturbances. Using a simple lumped parameter model as a guide, the analog frequency responses were curve fitted to obtain the inlet transfer functions for control purposes.
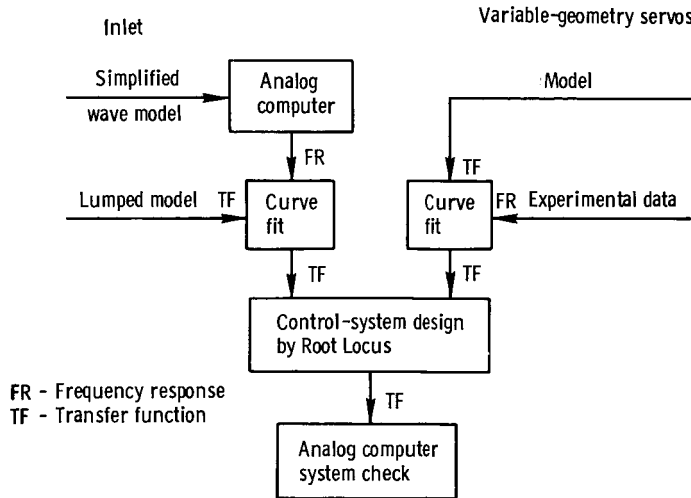
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Figure 3. - Inlet control systems investigation, analysis, and design.

The experimental frequency responses of the inlet controls hardware were also curve fitted using analytical models as guides to obtain their transfer functions. The inlet and controls hardware transfer functions were subsequently utilized in a root-locus procedure to design the normal shock controllers. The characteristics of the entire system were then verified on the analog computer.

Figure 4 illustrates the transfer function chosen to represent the inlet dynamics for control purposes. The transfer function is written in a form where both first and second order terms are expressed in a manner to indicate the S-plane location of their singularities. Thus, the poles and zeros are written as a magnitude and angle. The magnitude
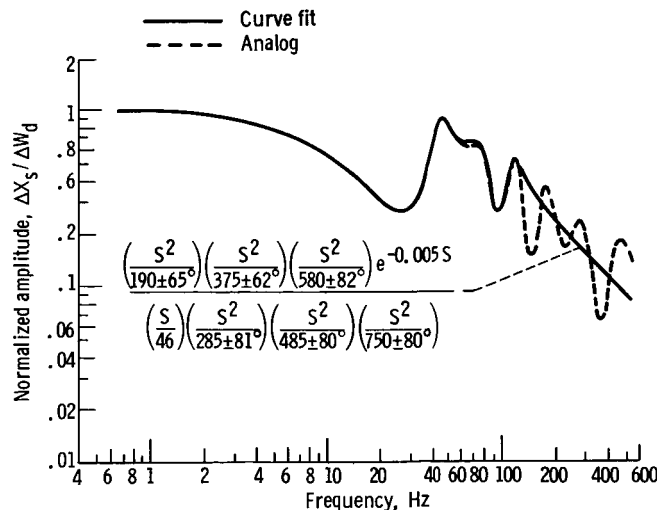

Figure 4. - Inlet transfer function for root locus analyses. Curve fit from analog wave simulation.

is the radial distance from the origin and the angle is measured from the negative real axis. The magnitude is numerically equal to the undamped natural frequency and the cosine of the angle is the damping ratio. The solid curve shows the response of the curve fit transfer function obtained by substituting $j\omega$ for the Laplace transform variable S. The dashed curve indicates the results from the analog simulation of the wave equations. Both responses represent the amplitude of shock motion, normalized to the 1-hertz value, produced by downstream flow disturbances for the inlet terminated with the cold pipe. This model adequately predicted the performance of the various normal shock control systems.

Experimental Results

Several types of control systems were examined analytically. Specific designs were selected from these for experimental testing on the inlet.

Single loop control. - Figure 5 illustrates the experimentally obtained performance of two single loop systems subjected to downstream flow disturbances. Throat exit static pressure (P_2) was used as the feedback signal. This signal adequately represents normal shock motion amplitude over the frequencies tested (see ref. 2). The P_2 signal was within 3 decibels of the normal shock motion up to 90 hertz.

The solid curve indicates the normalized response of the uncontrolled inlet when subjected to a sinusoidal exit area variation of 2.05×10^{-3} square meters peak to peak. Unity normalized amplitude represents a sinusoidal shock motion of 7.62×10^{-2} meters peak to peak, which caused a 7.52×10^{3} newtons per square meter peak-to-peak variation in throat exit static pressure (P_2).
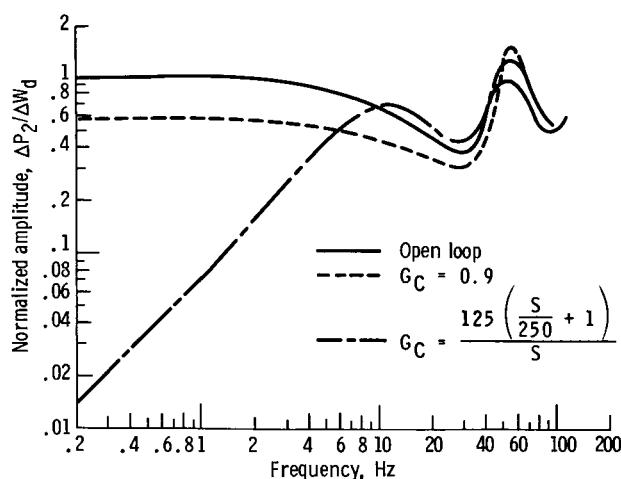

Figure 5. - Normal shock control. Throat-exit-static-pressure feedback only; Downstream disturbance; coldpipe.

The dashed curve illustrates the performance of a simple proportional controller. , The controller gain indicated produces a 40 percent reduction in shock motion at low frequencies; however, the inherent inlet resonance at 55 hertz is aggravated slightly. Use of higher gains with this system, to improve the low frequency response, would sensitize the inlet to disturbances near the resonance and would eventually produce instability.

The broken curve illustrates the performance of a proportional plus integral controller using the same feedback variable (P_2). This controller exhibits the desirable low frequency characteristics of integral control with a 93 percent reduction of shock motion at 1 hertz. In the regime from 8 to 140 hertz, this control system is slightly more sensitive to downstream disturbances than the uncontrolled inlet.

Multi-loop compensated control. - Root-locus analyses suggested the desirability of a compensated integral controller as indicated in figure 6. This system uses throat exit
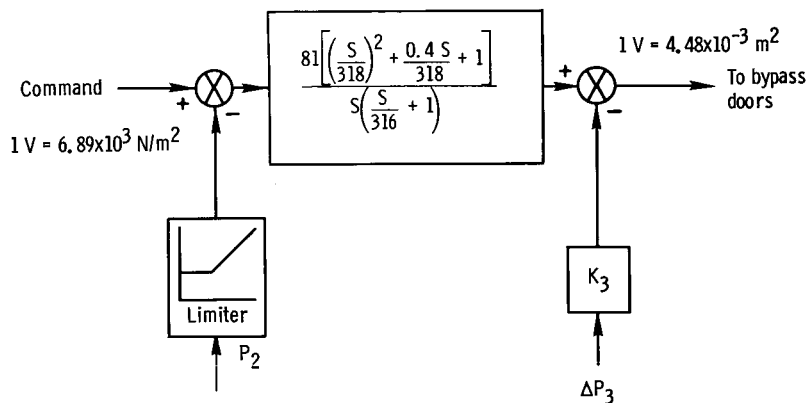

Figure 6. - Normal shock control-block diagram. Compensated integral controller.

static pressure (P_2) as the primary feedback variable. In addition, diffuser exit static pressure (P_3) is utilized in a minor feedback loop. This pressure serves as an anticipatory signal for downstream disturbances. The Δ indicates the use of a high pass filter in this loop, which was used to eliminate the dc component of the P_3 feedback signal.

The limiter, used in the outer loop, prevents control loop instability. It is needed because of an inflection point in the throat exit static pressure (P_2) against shock position curve.

Figure 7 indicates the performance of the compensated integral control when subjected to downstream disturbances. To illustrate the effect of the anticipatory loop, the responses are shown for three values of minor loop gain. As evidenced here, diffuser exit pressure feedback produces significant reduction of shock motion in the midfrequency regime. The solid curve indicates the best performance obtained with this type of control. Accordingly, it was selected for further testing.
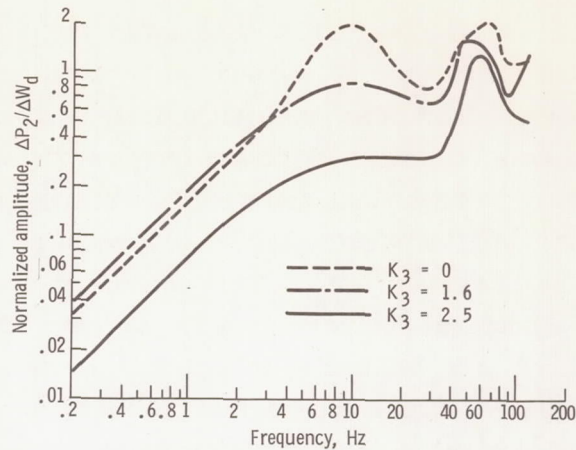
Figure 7. – Normal shock control. Anticipatory feedback; down-stream disturbance; coldpipe.
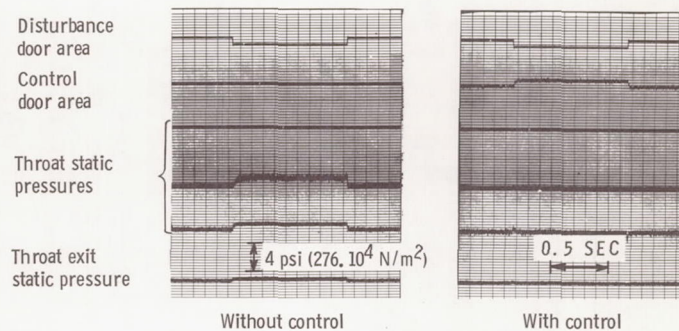

Figure 8. – Downstream disturbance transient. Choke plate ter-mination.

Figure 8 illustrates the transient response of the inlet to a step disturbance in bypass door area. Shown are two transients, one a step decrease in disturbance door area and the other a step increase 1 second later. The step had an amplitude of 2 percent of the choke plate exit area and took about 1.6 milliseconds. The response of the uncontrolled inlet is compared to that with the compensated integral normal shock control. Static pressures located 3.8, 7.2, and 8.9 centimeters aft of the geometric throat are shown in addition to the primary feedback signal (P_2). For this amplitude of disturbance the in-duced shock motion evidenced in the uncontrolled inlet is reduced to a momentary pulse of the downstream throat static pressure in the controlled inlet.

Termination effects. - Since the dynamics of the uncontrolled inlet are affected by the type of termination (ref. 2), the normal shock control system was tested with each termination. Figure 9 illustrates the performance of the two-loop, compensated-integral controller for downstream flow disturbances. The solid curve was obtained with the large volume cold-pipe termination, as previously shown in figure 7. The dashed curve illus-
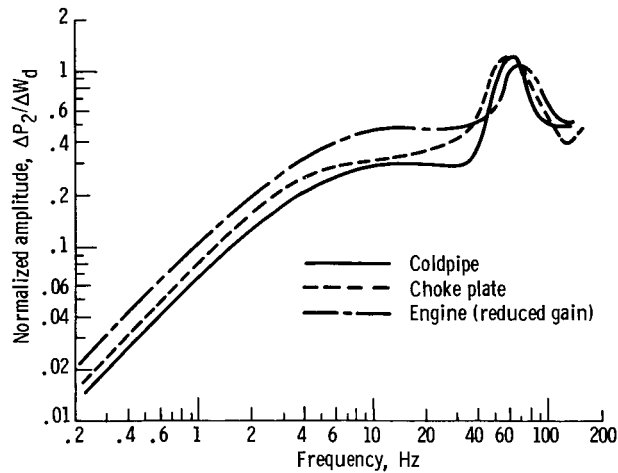
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Figure 9. - Normal shock control. Termination effect, down-
stream disturbance.

trates the performance of the same control system with the choke-plate termination. The
broken curve was obtained from the inlet coupled to the J-85-13 turbojet engine. The
same controller was used with the engine but the gain was slightly reduced.

The results indicate that the performance of the two-loop, compensated-integral con-
trol is relatively unaffected by the inlet termination. This is desirable since the input
impedance of turbojet engines can vary as a function of the operating point.

Upstream disturbances. - The performance of the normal shock control system sub-
jected to upstream disturbances is shown in figure 10. The gust plate was oscillated $\pm 1^{\circ}$
to 20 hertz. This produced a 4.46×10^3 newtons per square meter peak-to-peak variation
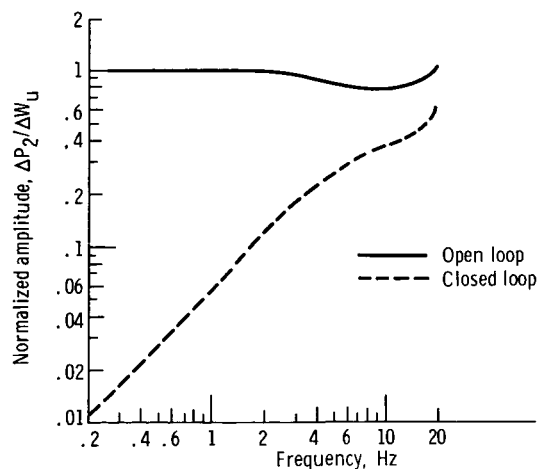in P_2 at 1 hertz. The solid curve shows the shock motion produced in the uncontrolled

Figure 10. - Normal shock control. Upstream dis-
turbance, choke plate.

inlet as indicated by normalized throat exit static pressure. The dashed curve indicates the response of the controlled inlet. A 95 percent reduction in shock motion was realized at 1 hertz. The response of the gust plate limited the frequency range investigated. For this test, the disturbance doors were stationary and the control doors were manipulated. It should be pointed out that since only the bypass doors were manipulated in this control system, regulation against large changes in free-stream Mach number was excluded.

RESTART CONTROL

Although the control systems previously discussed provide effective regulation of the started inlet, additional capabilities are required in the event of an inlet unstart. Unaware of the inlet unstart, the normal shock control would close the bypass doors in an attempt to maintain the desired throat exit static pressure. This action would contribute to inlet buzz, an unstable unstarted condition characterized by oscillatory flow.

Conventional restart controls disable the normal shock control system and open the bypass doors upon sensing an inlet unstart. This technique stabilizes the inlet by choking the throat. Concurrently, the centerbody is translated or collapsed to increase the throat area to a value which allows reswallowing of the normal shock. The normal shock control is subsequently reactivated at the completion of the restart cycle.

To insure choking of the throat, the bypass door opening should be of sufficient magnitude to allow for the reduced engine airflow which would result from an engine stall. Although this would allow successful restarting of the inlet, excessive bypass door opening would cause high-distortion levels in the inlet, particularly subsequent to restart when the normal shock would reach an extreme supercritical location. In addition, the pressure recovery during the restart cycle would be less than that potentially attainable.

An investigation was conducted to develop a restart control which would maintain closed loop control of the bypass doors throughout the restart sequence. Such a control would make it possible to achieve close to the highest possible pressure recovery throughout the restart cycle. An additional benefit is indicated in reference 3 which shows that the inlet airflow distortion at the engine face is minimized when pressure recovery is maximized. Since this type of control would entail feedback of inlet aerodynamic signals, it was necessary to ascertain the dynamic characteristics of the unstarted inlet. An experimental frequency response of the unstarted inlet indicated that the inherent open-loop dynamics were similar to those of the started inlet. Thus, the regulation of the secondary normal shock formed in the unstarted inlet, as well as internal pressures, could be accomplished by a method similar to that previously used.

Figure 11 illustrates the performance of a normal shock control system with the inlet started and unstarted. The unstarted and started tests were conducted with the inlet terminated by the choke plate and engine, respectively. Although the terminations were not identical, it was previously demonstrated that the inlet dynamics are similar for these
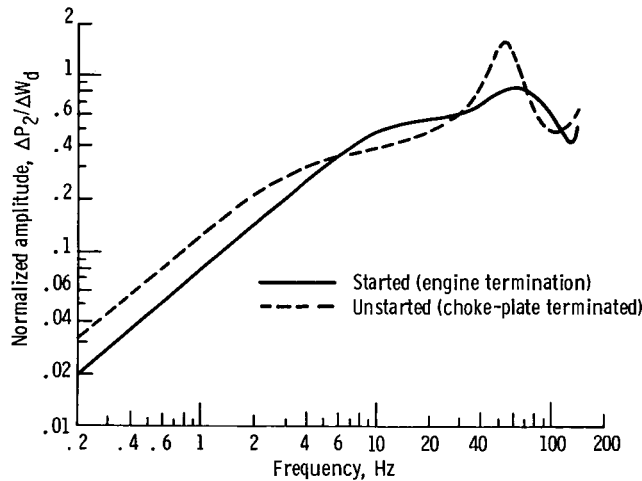
Figure 11. - Normal shock control. Inlet started and unstarted, downstream disturbance.

terminations. The unstarted inlet exhibits a more pronounced resonance at 55 hertz, but the gross dynamic characteristics are similar to those of the controlled started inlet. It was, of course, necessary to lower the throat exit static pressure setpoint for the unstarted inlet. The results indicated in the figure suggested that previously developed normal shock control systems could be utilized to control the bypass doors during the restart cycle.

Figure 12 shows a schematic representation of the restart control which was investigated. The inlet was terminated with the large volume cold pipe. The normal shock control system utilized the compensated integral controller, without minor loop feedback. During both started and unstarted operation of the inlet, the command to the normal shock controller was scheduled as a function of centerbody position.
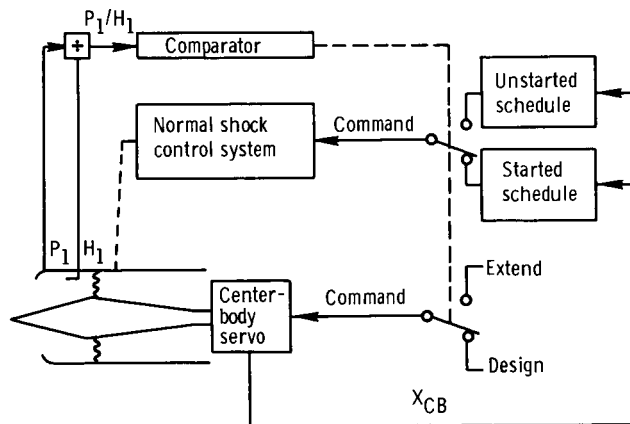

Figure 12. - Restart control.

The ratio of a cowl lip static-to-throat total was used to detect unstart. If this signal exceeded a predetermined value, the comparator relay switched to the unstart state. The command to the shock control was then determined by the unstarted schedule. This schedule commanded a value of throat exit static pressure which was sufficiently low to be attainable with the inlet unstarted. At the same instant, the centerbody was extended at its maximum slewing rate to increase the throat area. During the translation of the centerbody, the throat exit static pressure command was scheduled to increase as a function of centerbody position.

The instant restart was sensed, the comparator returned the shock control command to the started schedule and reversed the travel of the centerbody. As the centerbody retracted, the started schedule continued to increase the commanded value of throat exit static pressure. This prevented excessive supercritical shock positions during the cycle. Automatic positioning of the bypass doors during the entire restart cycle was accomplished with this system.

The unstarted schedule was experimentally obtained by dividing the centerbody travel into finite intervals and individually adjusting the shock control command for each interval. The setpoint selected for each interval was within 3.45×10^3 newtons per square meter of the maximum attainable value for stable operation. The started schedule was obtained in the same manner.

A typical unstart transient, followed by a controlled restart cycle, is shown in figure 13. The arrows indicate increasing values of the variables. The three lower traces are pressure signals derived from taps at fixed locations on the cowl. When the centerbody translates, the throat moves with it. This changes the location of the taps with re-
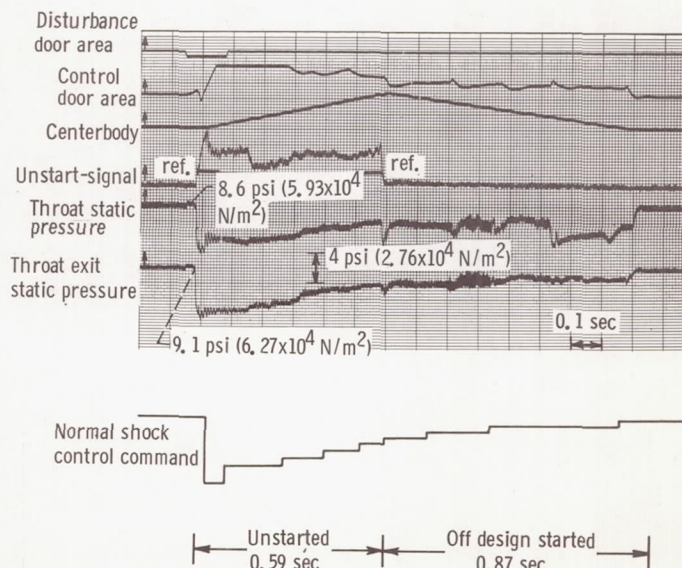
Figure 13. - Controlled restart.

spect to the throat during the restart sequence.

The normal shock was initially positioned just aft of the throat static tap on the verge of unstart by the closed-loop bypass control. A pulse-type decrease in disturbance door area initiated the inlet unstart. The initial increase in control door area indicates the attempt of the normal shock control to prevent the unstart. Unable to prevent the unstart and responding to the decreasing pressure, the normal shock control erroneously began to close the control doors.

When the unstart signal exceeded the reference value, the normal shock control command signal was switched to the unstarted schedule. This caused the control door area to increase to attain the lower commanded value of throat exit static pressure. At the same time the centerbody was extended.

The control door area remained full open until the feedback value of P_2 coming from the limiter dropped below the commanded value. The normal shock controller then adjusted control door area to attain the scheduled command pressure. The centerbody was extended until restart was indicated by the unstart signal dropping below the reference value. At that time centerbody travel was reversed.

Upon restart, the ingested normal shock was located between the throat static and P_2 taps. This was indicated by the large instantaneous drop in the throat static and a relatively small drop in P_2. The normal shock controller then followed the started schedule of the command signal. The control door area was decreased, moving the terminal shock upstream of the throat static. As the centerbody returned to design, the normal shock again moved downstream of the throat static, due to the translation of the geometric throat. With the centerbody back on design, the normal shock returned to the operating point as indicated by the pressure levels in the inlet. The total restart cycle took 1.46 seconds which was limited by centerbody slewing rate. A continuous schedule of the command signal was also used successfully. The continuous schedule was implemented using a diode function generator.

The restart control system was designed for research purposes only and was not intended to work at all altitudes, Mach numbers, angles of attack, etcetera. For this reason, the control command signal P_2 was not normalized. The restart control system was tested at Mach 2.5, 2.3, and 2.0 with a pulse-type unstart disturbance. The control successfully restarted the inlet in all cases.

CONCLUDING REMARKS

This investigation determined the performance characteristics of normal shock control systems which utilized high-performance bypass doors. Significant reduction of downstream disturbance induced shock motion was achieved over the frequency range of

0 to 40 hertz with a two-loop, compensated-integral controller. Analysis and design of this system required consideration of the inherent inlet dynamics to 100 hertz. Reduction of the inlet resonance at 55 hertz was not accomplished by the control systems investigated. Significant reduction of shock motion to upstream disturbances was obtained below 10 hertz. Adequate control of the normal shock was maintained, whether the inlet was terminated by a large volume cold pipe, choke plate at the engine face, or a J-85-13 turbojet engine.

The ability of the system to control the secondary shock in the unstarted inlet led to the development of a restart control which featured closed-loop positioning of the bypass doors. This was achieved by scheduling the normal shock control command as a function of centerbody position for both started and unstarted conditions. This type of control maximized pressure recovery and tends to minimize inlet distortion during the restart cycle.

Lewis Research Center,
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