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TECHNICAL PAPER proposed for presentation at the Fourth Joint Propulsion Specialists Conference sponsored by the American Institute of Aeronautics and Astronautics Cleveland, Ohio, June 10-14, 1968

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Abstract

Results from investigations of normal shock and restart control systems utilizing 100 Hz bypass doors and 250 Hz pressure transducers are presented. Included are analyses followed by experimental results obtained from a 25-inch 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 downstream and upstream flow disturbances from 0 to 140 Hz and 0 to 20 Hz, respectively. 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 performance with electronic compensation and use of multiple feedback. The restart controllers maintained closed-loop bypass door control throughout the restart cycle. This minimized total pressure variations at the engine face station.

I. 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 upstream 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 aerodynamic 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.

II. Apparatus and Procedure

The inlet selected for this investigation was a 25-inch, axisymmetric model. 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.

A schematic representation of the inlet 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 Hz and exhibited flat response to 100 Hz.

Close coupled dynamic pressure transducers were utilized for data and control. Their frequency response was approximately 250 Hz. Those signals used for control are indicated on the Figure. 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 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 Hz to provide a symmetric downstream flow disturbance. An oscillating plate located upstream of the inlet produced gust-like disturbances to 20 Hz.

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.

III. 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. An analog computer simulation of inlet dynamics, and the steady state inlet characteristics,(1) were available, however.

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Figure 2 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.

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 3 illustrates the transfer function chosen to represent the inlet dynamics for control purposes. 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 normalized amplitude of shock motion 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 4 illustrates the 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.

The solid curve indicates the normalized response of the uncontrolled inlet. Unity normalized amplitude represents a sinusoidal shock motion of 3 inches peak to peak.

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. The inherent inlet resonance at 55 Hz is aggravated slightly, however. 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 Hz.

In the regime from 8 to 140 Hz, this control system is slightly more sensitive to downstream disturbances than the uncontrolled inlet.

Multiloop compensated control. - Root locus analyses suggested the desirability of a compensated integral controller as indicated in Figure 5. This system uses throat exit 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.

The limiter, used in the outer loop, prevents the occurrence of positive feedback should the normal shock pass downstream of the throat exit static tap.

Figure 6 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 mid-frequency regime. The solid curve indicates the best performance obtained with this type of control. Accordingly, it was selected for further testing.

Figure 7 illustrates the transient response of the inlet subjected to a 1.6-millisecond step of exit area, using the disturbance bypass doors. The response of the uncontrolled inlet is compared to that with the compensated integral normal shock control. Three throat static pressures are shown in addition to the primary feedback signal, P_2. The disturbance induced shock motion evidenced in the uncontrolled inlet is reduced to a momentary pulse of the downstream throat static pressure. The magnitude of the disturbance was approximately 2 percent of design airflow.

Termination effects. - Since the dynamics of the uncontrolled inlet are affected by the type of termination,[2] the normal shock control system was tested with each termination. Figure 8 illustrates the performance of the two-loop, compensated integral controller for downstream flow disturbances. The solid curve was obtained with the cold pipe termination, as previously shown in Figure 6. The dashed curve illustrates 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 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 control 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 subjected to upstream disturbances is shown in Figure 9. The gust plate was oscillated plus and minus 1 degree to 20 Hz. The solid curve shows the shock motion produced in the uncontrolled 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 Hz. The response of the gust plate limited the frequency range investigated. It should be pointed out that only the bypass doors were manipulated in this control system, which excludes regulation against large changes in Mach number.

IV. 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 maintained closed loop control of the bypass door throughout the restart sequence. 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 10 illustrates the performance of the two-loop compensated integral normal shock control system with the inlet started and unstarted. Although the unstarted inlet exhibits a more pronounced resonance at 55 Hz, 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 the previously developed normal shock control could be utilized to control the bypass doors during the restart cycle.

Figure 11 shows a schematic representation of the restart control which was investigated. The normal shock control system utilized the compensated integral controller, previously discussed. During started operation of the inlet, the command to the normal shock controller was scheduled as a function of centerbody position. At the design operating point, the command was constant.

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 continuously increase to the maximum stable value obtainable at each 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. For each centerbody position the started schedule commanded the maximum obtainable 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 highest stable value was selected for each interval. The started schedule was obtained in the same manner.

A typical unstart transient, followed by a controlled restart cycle, is shown in Figure 12. The arrows indicate increasing values of the variables.

The normal shock was initially positioned 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 measured value of throat exit static pressure, P_2, 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 the centerbody was reversed.

Upon restart, the normal shock first formed 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, because the inlet throat was fixed relative to the centerbody. 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 as limited by centerbody slewing rate.

A continuous schedule of the command signal was also used successfully. The continuous schedule was obtained by 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, etc. 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. At Mach 2.5 the control was also subjected to step and square wave unstart disturbances. The control successfully restarted the inlet in all cases.

V. Concluding Remarks

This investigation determined the performance characteristics of normal shock control systems which utilized high performance bypass doors. Significant reduction of disturbance induced shock motion was achieved over the frequency range 0 to 40 Hz with a two-loop, compensated integral controller. Analyses and design of this system required consideration of the inherent inlet dynamics to 100 Hz. Reduction of the inlet resonance at 55 Hz was not accomplished by the control systems investigated. The performance achieved was similar for downstream and upstream disturbances over the frequencies tested. 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 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 minimized distortion and maximized pressure recovery during the restart cycle.

References

1. Cubbison, R. W.; Meleason, E. T.; and Johnson, D. F.: Effect of Amount and Location of Porous Bleed in a High Performance Axisymmetric Mixed Compression Inlet at Mach 2.5. Proposed NASA TM, National Aeronautics and Space Administration, Cleveland, Ohio.

2. Wasserbauer, J. F.; and Willoh, R. G., Jr.: Experimental and Analytical Investigation of the Dynamic Response of a Supersonic Mixed-Compression Inlet. Paper presented at Fourth Propulsion Joint Specialist Conference, June 1968, AIAA, Cleveland, Ohio.

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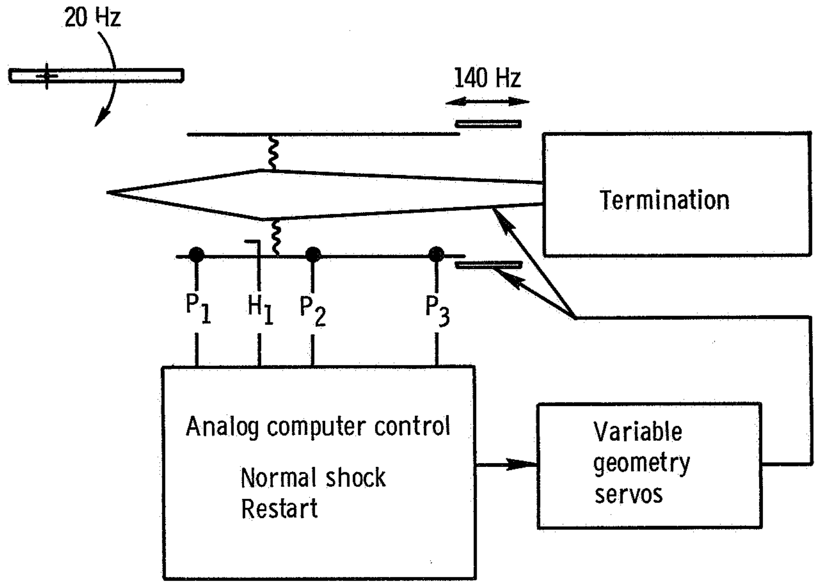

Figure 1. - Inlet control experiment.

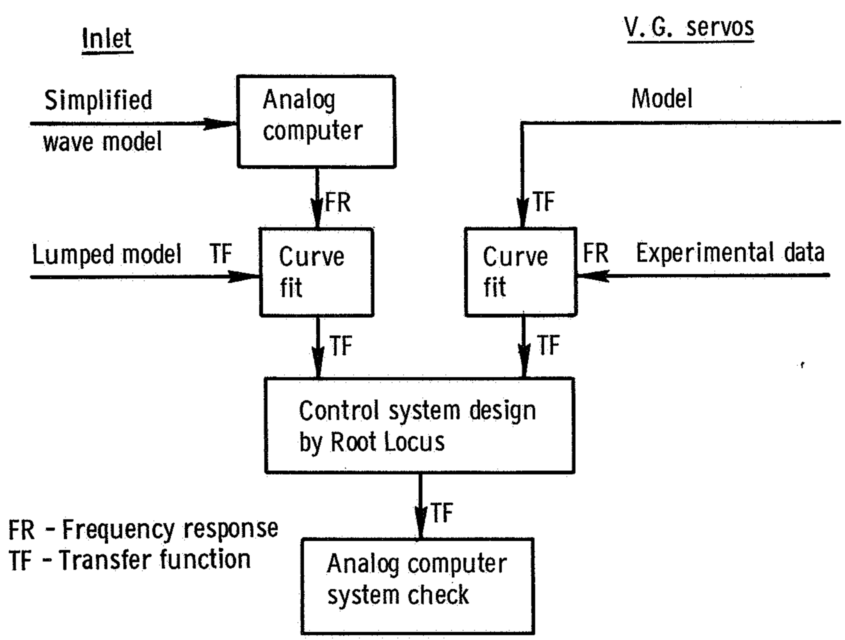

Figure 2. - Inlet control systems investigation, analyses and design.

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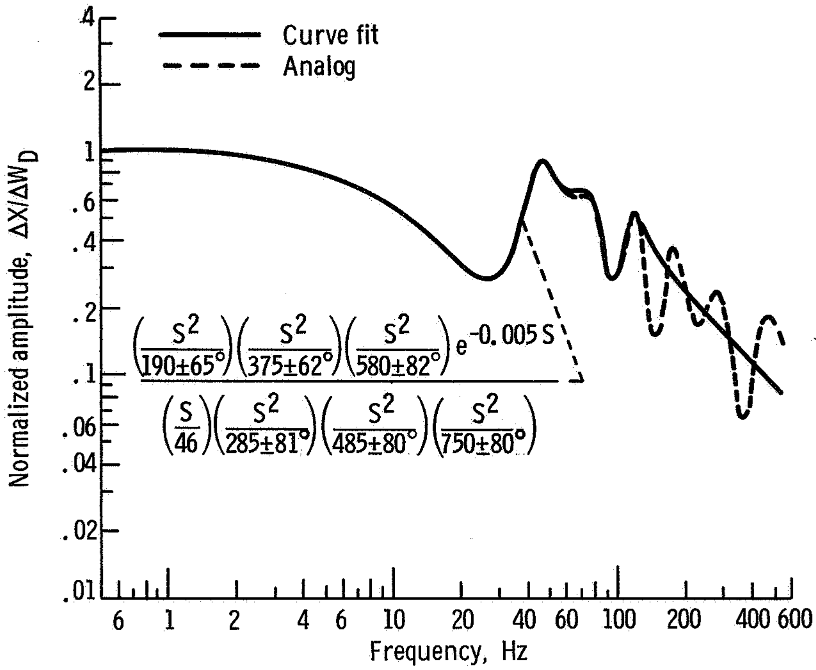

Figure 3. - Inlet transfer function for root locus analyses. Curve fit from analog wave simulation.

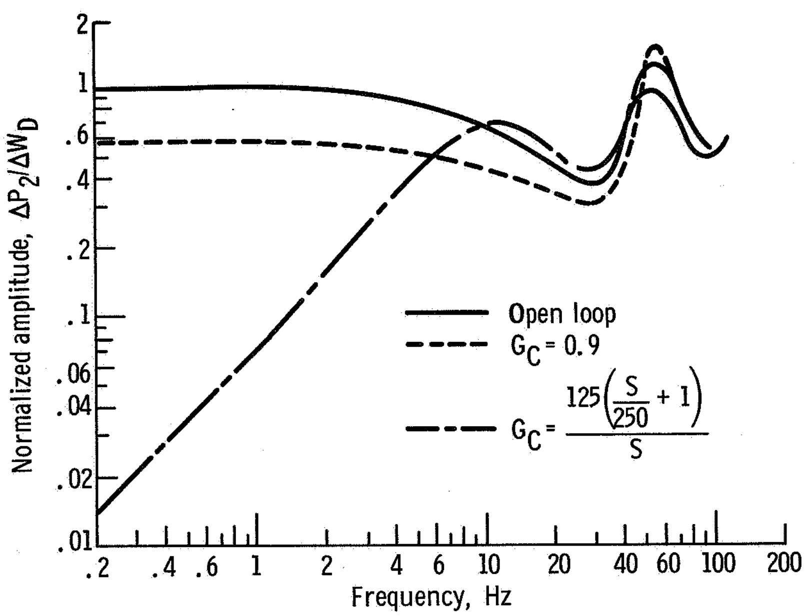

Figure 4. - Normal shock control - P_2 feedback only. Downstream disturbance - coldpipe.

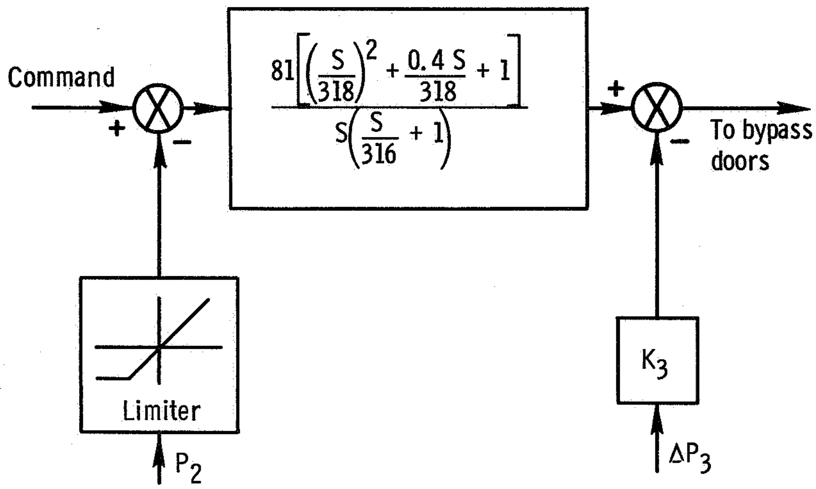

Figure 5. - Normal shock control-block diagram. Compensated integral controller.

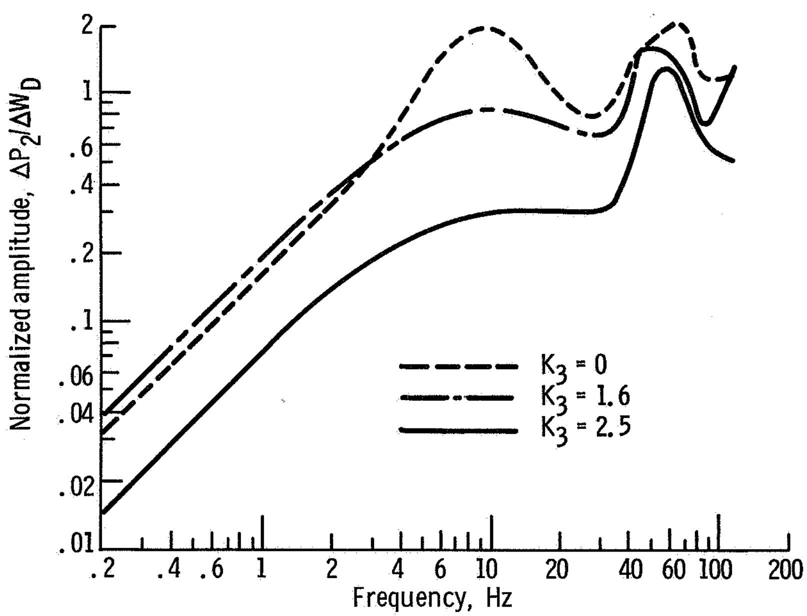

Figure 6. - Normal shock control - anticipatory feedback, downstream disturbance - coldpipe.

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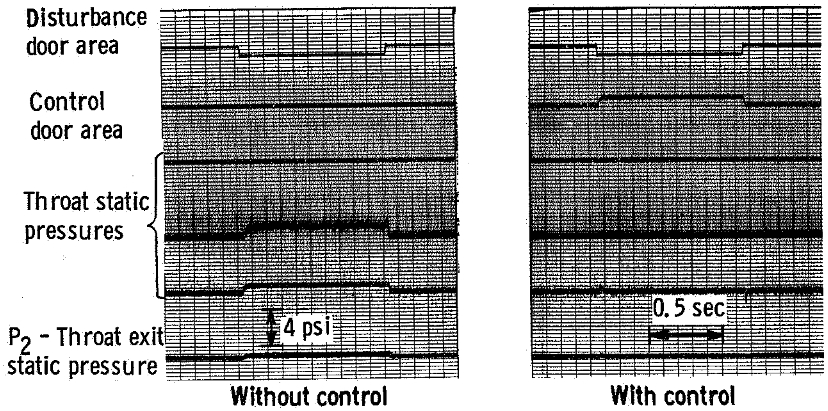

Figure 7. - Downstream disturbance transient - choke plate termination.

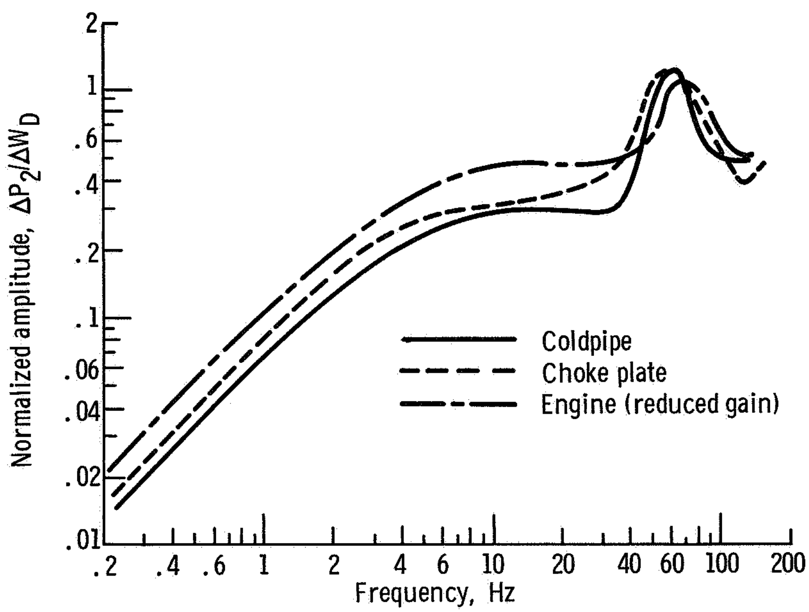

Figure 8. - Normal shock control - termination effect, downstream disturbance.

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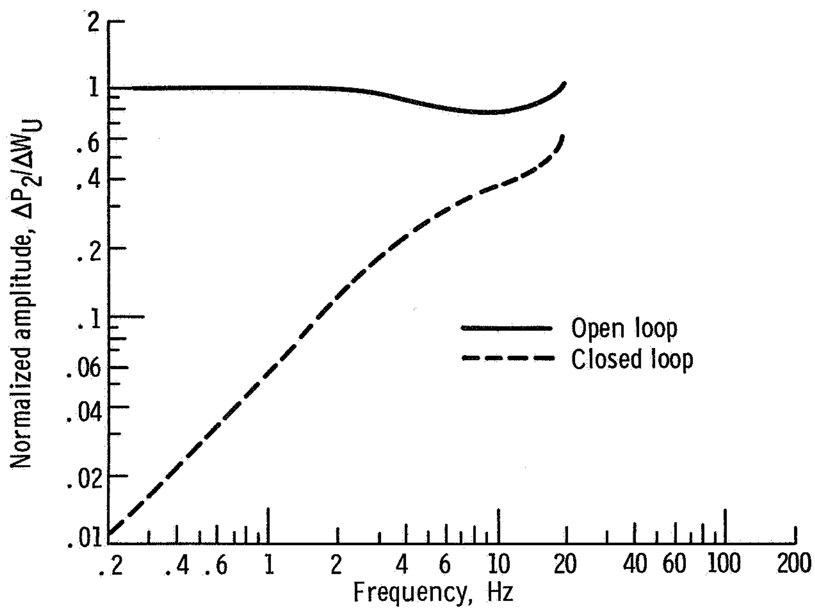

Figure 9. - Normal shock control - upstream disturbance, choke plate.

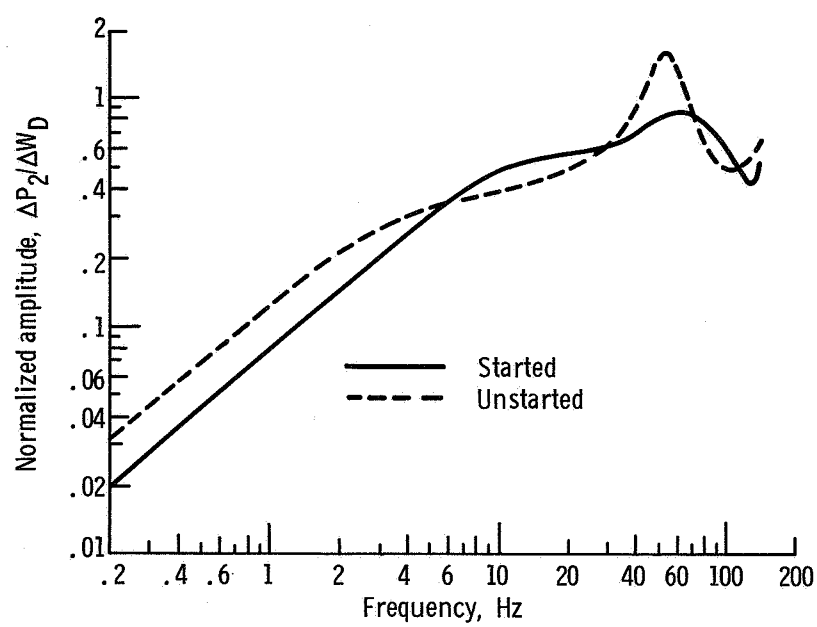

Figure 10. - Normal shock control - inlet started and unstarted, downstream disturbance - choke plate.

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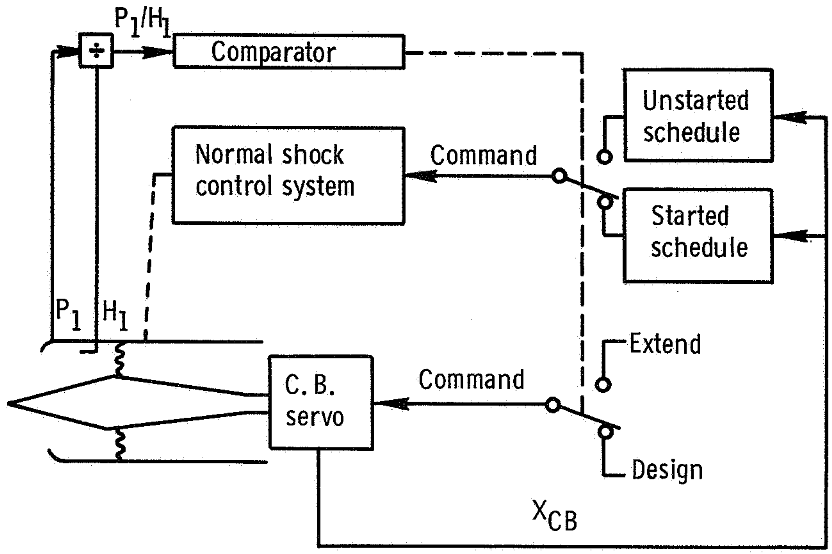

Figure 11. - Restart control.

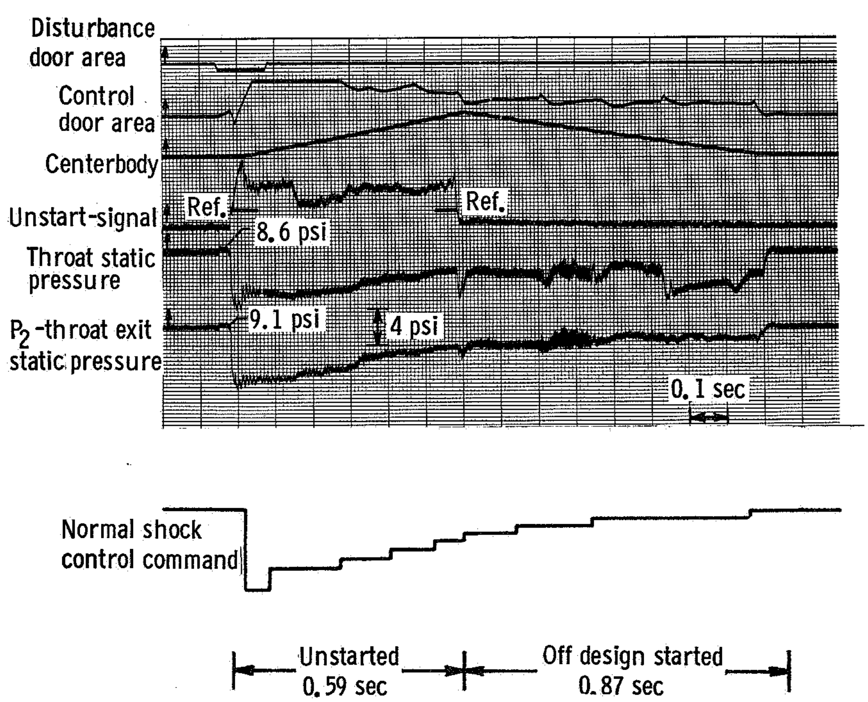

Figure 12. - Controlled restart.