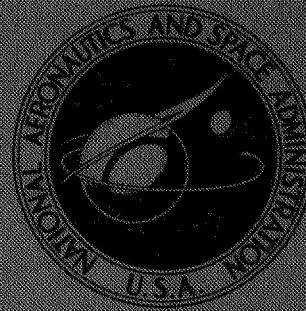


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TERMINAL-SHOCK AND RESTART CONTROL
OF A MACH 2.5, AXISYMMETRIC,
MIXED-COMPRESSION INLET WITH
40-PERCENT INTERNAL CONTRACTION

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SUMMARY

Results of experimental tests conducted on a supersonic, mixed-compression, axisymmetric inlet are presented. The inlet is designed for operation at Mach 2.5 with a turbofan engine (TF-30). The inlet was coupled to either a choked orifice plate or a long duct which had a variable-area choked exit plug.

Closed-loop frequency responses of selected diffuser static pressures used in the terminal-shock control system are presented. Results are shown for Mach 2.5 conditions with the inlet coupled to either the choked orifice plate or the long duct. Inlet unstart-restart traces are also presented. High-response inlet bypass doors were used to generate an internal disturbance and also to achieve terminal-shock control.

The results show the closed-loop frequency response (with proportional-plus-integral control) of diffuser static pressures is below the open-loop frequency response out to about 10 hertz when the inlet is coupled to the choked orifice. But, with the inlet coupled to the long duct, improved low-frequency attenuation is obtained at the expense of large midfrequency resonant amplitudes. Closed-loop frequency responses of the feedback pressure used in the terminal-shock position control system are shown for the inlet coupled to both the choked orifice and the long duct.

Unstart-restart traces are shown for the inlet with and without terminal-shock control. Inlet restart times are governed by the slewing rate of the spike. Restart cycles take approximately 2 seconds.

INTRODUCTION

The function of the supersonic inlet is to convert kinetic energy of the supersonic stream to static-pressure rise at the engine compressor face with minimum losses and low distortion. Since maximum pressure recovery and low distortion levels are achieved

with the terminal shock located just downstream of the inlet throat, inlet controls are needed to prevent shock displacement from this point. An automatic restart control is also needed to restart the inlet in case of an unstart and to return the inlet to its operating point.

Past programs on inlet controls conducted at the Lewis Research Center are reported in references 1 and 2. Reference 1 presents results of a controls program conducted on a Mach 2.7, two-dimensional, mixed-compression inlet. Reference 2 presents results on a controls program conducted on a Mach 2.5, axisymmetric, mixed-compression inlet. An example of work done in industry on inlet controls is presented in reference 3.

An inlet program was run in the Lewis 10- by 10-foot supersonic wind tunnel on an axisymmetric, mixed-compression inlet designed for Mach 2.5 operation with a TF-30 engine. This program consisted of two parts. The first part was an open-loop dynamics study in which the critical frequencies of the inlet were identified (ref. 4). The second part dealt with developing a terminal-shock control. This report presents the results of the terminal-shock control program.

The open-loop program showed that coupling the inlet to a long duct which is terminated with a choked exit plug produces resonances at approximately 30 and 60 hertz in the response of selected inlet diffuser static pressures to bypass airflow disturbances. When the inlet is coupled to a choked orifice plate located at the compressor face station, the first resonance is moved to beyond 100 hertz. The terminal-shock position is more sensitive to downstream disturbances when the cowl bleeds are sealed. This means that a given internal disturbance would result in larger shock displacements than would occur with cowl bleeds open.

Results presented in this report are for Mach 2.5 operating conditions with the inlet coupled to a choked orifice with sealed cowl bleeds and with the inlet coupled to a long duct with the nominal bleed configuration. Closed-loop frequency responses of the terminal-shock control system using either of two averaged diffuser static pressures as the control parameter are presented. Analytical expressions for the open-loop inlet dynamics are also presented. These were obtained by curve fitting experimental frequency response data to transfer functions. Inlet unstart-restart traces, with and without terminal-shock control, are also presented.

SYMBOLS

A	bypass door area, sq cm
Gc	transfer function (see fig. 7), volts/(N/sq cm)
Gd	transfer function (see fig. 7), sq cm/volt

G1	transfer function (see fig. 7), $N/(\text{sq cm}) (\text{sq cm})$
G2	transfer function (see fig. 7), dimensionless
G3	transfer function (see fig. 7), $\text{cu cm}/N$
P	total pressure, $N/\text{sq cm}$
p	diffuser static pressure, $N/\text{sq cm}$
s	Laplace operator, $1/\text{sec}$
v	electrical signal, volts

Subscripts:

cl	cowl-lip static pressure
ref	reference signal
tt	throat total pressure
56	transducer located 56.8 cm from cowl lip
66	transducer located 66.9 cm from cowl lip

Superscript:

— average value

APPARATUS AND PROCEDURE

Model

The inlet, shown in figure 1 is an axisymmetric, mixed-compression inlet with translating center body and with 40-percent internal supersonic area contraction. The inlet is designed for Mach 2.5 operation with a TF-30 engine. The inlet has a capture area of 7070 square centimeters and measures 180 centimeters from the cowl lip to the compressor face. Provisions are made for boundary-layer bleeds on the center body and cowl. Porous bleeds are located on the cowl, and the flow is ducted overboard. The center-body bleed is a slot type bleed. The center-body bleed flow is ducted to four equally spaced struts located in the diffuser section. Center-body bleed flow is controlled by an electric-motor-actuated butterfly valve in each strut. The inlet was

tested with a cowl bleed configuration determined in a steady-state program (unpublished data) and also with the cowl bleeds sealed.

The inlet is equipped with eight overboard bypass doors used to match inlet and engine airflow. Figure 2 shows a cross section of the diffuser indicating the location of the bypass doors and the center-body flow struts.

All tests were run at zero angle of attack. The inlet was alternately coupled to a choked orifice located at the compressor face station and a long duct (487 cm in length) which was terminated in a remotely controlled choked plug. The response of the inlet diffuser static pressures with the inlet coupled to the engine would be expected to fall between the response of these pressures when the inlet is coupled to the choked orifice or the long duct.

Frequency response data were obtained for terminal-shock operating points located 2.54 to 8.87 centimeters from the inlet throat. Inlet and tunnel conditions for this program are listed in table I.

Disturbance Device

Internal airflow disturbances are produced with the inlet overboard bypass doors. Two of the eight bypass doors can be seen in figure 1. The bypass door is a sliding plate valve driven by a high-response electrohydraulic servovalve actuator assembly. Each door has an open area of 404 square centimeters for a linear displacement of 2.54 centimeters. Detailed information on the bypass doors used in this test program is presented in reference 5. Reference 6 contains detailed information of the design of electrohydraulic servosystems.

Door pairs (1 and 5 or 3 and 7) were used to provide the internal disturbance. The zero-to-peak disturbance amplitude was 3 percent of full stroke. The frequency response of door motion to a sinusoidal input signal was flat to 100 hertz. When doors 1 and 5 were used for the disturbance, doors 3 and 7 were used as the control doors.

Instrumentation

Linear motion of the bypass door is measured by a linear variable differential transformer (LVDT). The transducer has negligible dynamics in the frequency range covered in these tests (0.1 to 100 Hz).

Figure 3 is a sketch of the inlet showing the pressure instrumentation locations. Steady-state pressure instrumentation was used to measure the terminal-shock position. This was done by moving the shock far into the supercritical region and defining the supersonic profile of the inlet. The terminal-shock location was established by noting

which of the transducers in the string first read a higher pressure than the supersonic value. There are 16 steady-state transducers located 23 to 66 centimeters from the cowl lip. The 14 most upstream transducers are spaced 2.54 centimeters apart. The last two transducers are spaced 5.08 centimeters apart.

The time varying pressures were measured with strain-gage type transducers connected to the cowl with short tubes. The frequency response of the pressure measuring system had negligible dynamics in the range covered in these tests (0.1 to 100 Hz). As shown in figure 3, the planes containing the dynamic instrumentation are located 56 and 66 centimeters from the cowl lip. Each plane contains four transducers spaced 90° apart. The four pressures in each plane were electrically averaged. The average pressures are identified as p_{66} and p_{56} . The locations of the geometric throat and cowl bleeds in the subsonic region are shown in figure 3.

Data Acquisition and Reduction

Frequency response data were taken by using sweep frequency techniques, and the data were stored on analog tape. The data were then reduced off line on a digital computer using methods described in reference 7. The data are presented for variations in two averaged inlet diffuser pressures in response to bypass door area variations. All frequency domain plots are normalized to the 0.1-hertz open-loop value. The open-loop data are presented as Bode plots. The closed-loop data are presented as normalized amplitude ratio only.

RESULTS AND DISCUSSION

Transfer-Function Identification

Knowledge of plant (system to be controlled) dynamics in transfer-function form helps to identify critical frequencies of the plant and aids in designing its control. The transfer functions for experimental frequency response data were obtained from a Lewis program which fits experimental data to some assumed frequency domain structure. The analytical transfer-function identification program with experimental open-loop of minimizing a least-square error cost function. The transfer-function structure is identified from a plot of the experimental data. The parameters of the transfer function which minimize the cost function are found by using a gradient search technique. Results shown in figures 4 and 5 compare the normalized amplitude ratios for p_{66} and p_{56} obtained from the transfer-function identification program with experimental open-loop frequency response data. The results shown in these figures are for Mach 2.5 condi-

tions with sealed cowl bleeds and with the inlet coupled to the choked orifice plate. The locations of the pressure transducers and the compressor face station are shown in figure 3. The data shown in figures 4 and 5 were obtained by using doors 3 and 7 as the disturbance doors. The transfer functions obtained for each frequency response plot are shown in the figures. The expressions obtained are fourth-order expressions in the frequency domain. The fourth-order system consists of two first-order terms and a second-order term. For the transfer function of \bar{p}_{66} (fig. 4) the first-order terms have corner frequencies at 6.67 and 403 hertz, and the second-order term has a damping ratio of 0.247 with a natural frequency of 89 hertz. For the transfer function of \bar{p}_{56} (fig. 5) the first-order terms have corner frequencies at 5.3 and 70.7 hertz, and the second-order term has a damping ratio of 0.244 with a natural frequency of 86 hertz. The lower corner frequencies for the amplitude ratio of \bar{p}_{56} are due in part to the additional volume between the two pressure measuring stations. The plots shown in figures 4 and 5 show no resonances occurring in the 1- to 100-hertz frequency range.

Results shown in figure 6 compare the results from a transfer-function identification program with experimental open-loop frequency response data for \bar{p}_{66} for the inlet operating at Mach 2.5 with cowl bleed and coupled to the long duct. These data were obtained by using doors 3 and 7 as the disturbance doors. The transfer function shown in figure 6 is much more complex than the expressions obtained for the inlet coupled to the choked orifice. The more complex expression is due to the addition of the long duct and indicates the existence of multiple resonances. These resonances, occurring at approximately 30 and 60 hertz, are due to the standing waves produced in the inlet and the long duct.

Terminal-Shock Control

A block diagram of the inlet shock position control system is shown in figure 7. This inlet is not equipped with a dynamic shock sensor, and therefore the shock position signal cannot be directly used as the control signal. Terminal-shock control is achieved by using a diffuser static pressure as the feedback control signal. The figure indicates pressure \bar{p}_{66} as the feedback control signal. Data are presented showing either \bar{p}_{66} or \bar{p}_{56} as the feedback control signal. The terminal-shock position is correlated with pressures \bar{p}_{66} and \bar{p}_{56} during steady-state operation. The steady-state terminal-shock location is obtained from the string of transducers shown in figure 3. Disturbances are introduced internally by varying the bypass door area. These disturbances result in a displacement of the shock from its nominal operating point and result in changes in pressures \bar{p}_{66} and \bar{p}_{56} . The change in pressure from its nominal value results in an error which is modified by the controller and drives the control bypass doors in a direction to compensate for the disturbance and reduce the error to zero.

The controller form chosen for this inlet system was obtained from a Lewis program which determines the controller transfer function by a gradient search of a least-square cost function of regulation error and a weighted penalty of bypass door energy expended upon measurement noise. The regulation error is a pressure (or terminal-shock) variation from the nominal due to disturbances in inlet airflow. Different controller parameter designs can be precalculated by varying the relative weighting of the bypass door noise response. The controller form chosen for this system was a proportional-plus-integral form because it results in zero steady-state error and provides desirable low-frequency attenuation. Ideally the controller would yield a closed-loop frequency response with zero amplitude ratio over the entire frequency range considered. Practically, however, the closed-loop response is a compromise between the desired low-frequency attenuation and acceptable resonant characteristics in the midfrequency range.

Closed-loop frequency responses shown in figure 8 are for the inlet operating at Mach 2.5 with no cowl bleeds and with the inlet coupled to the choked orifice plate. The results shown in figure 8 are for p_{66} and p_{56} used as control feedback signals. The open-loop normalized amplitude ratio frequency responses of these pressures are shown in this figure for comparison. The controller gains were varied to determine their effect on the closed-loop frequency response. In figure 8(a), the controller with the low proportional gain (0.065) shows closed-loop frequency response below open-loop response to approximately 6.5 hertz. For the low proportional gain case cited the closed-loop response shows a resonance at approximately 10 hertz with an amplification 30 percent above the steady-state value. As the controller gains increase, the closed-loop response crosses the open-loop response at a higher frequency with reduced resonant amplitude.

For the controller with proportional gain of 1.05 and integral gain of 126, the frequency at which the closed-loop response crosses the open-loop response has been extended to 10 hertz with a reduced resonant amplitude. Further increases in controller gains lead to an unstable step response.

Results shown in figure 8(b) are for pressure p_{56} used as the control feedback signal. The closed-loop response first crosses the open-loop response at approximately 10 hertz. The resonant amplitude is larger for the closed-loop response of p_{56} than it is for the case with p_{66} used as the control signal (for the same controller gains) because of the higher steady-state gain of p_{56} . The gain is higher because p_{56} is closer to the terminal shock. The locations of the measuring stations are shown in figure 3.

Results shown in figure 9 are for the inlet operating at Mach 2.5 with cowl bleed with the inlet coupled to the long duct. The results show both the open- and closed-loop response of pressure p_{66} . The closed-loop responses for various controller gains show the effect of adding the long duct to the inlet. As the frequency at which the closed-loop response first crosses the open-loop response is increased, larger reso-

nant amplitudes are introduced. For this inlet - long-duct combination a tradeoff between desired low-frequency attenuation and acceptable resonance amplitude must be made. The multiple resonances observed are due to standing waves produced in the inlet by the addition of the long duct.

Restart Control

A diagram of the restart control system is shown in figure 10. The ratio of cowl static to throat total pressure p_{cl}/P_{tt} was used as the unstart sensor. For the started condition this pressure ratio is low because the cowl static pressure is in a supersonic flow region (low static pressure) and the inlet pressure recovery is high. For the unstarted condition the pressure ratio is high because the cowl static pressure is in a subsonic flow region (high static pressure) and the inlet recovery is low. An unstart is detected when the p_{cl}/P_{tt} signal exceeds some reference value. When the inlet unstarts, the spike is commanded to extend and the pressure command signal to the bypass doors is switched to an unstarted value. The spike command and the bypass door pressure command are switched in through relays that are actuated by the unstart signal. The spike is extended when the inlet is unstarted to increase the throat to cowl-lip area ratio to permit restart of the inlet. The bypass doors are commanded to follow a schedule that causes them to open to prevent the unstable inlet condition known as buzz. When the inlet is restarted, the spike is commanded to return to its design value and the bypass door command is switched to the started schedule.

Two restart cycles are shown in figures 11 and 12. The inlet was coupled to the long duct and was operating at Mach 2.5. Unstarts, in both cases, were produced by stepping closed doors 3 and 7.

The restart cycle shown in figure 11 is for the inlet without terminal-shock control. The terminal-shock control was disconnected from the system, and the control doors (1 and 5) remained at their operating point. The sequence of events identified in figure 11 is as follows. The disturbance (1) is applied by stepping doors 3 and 7 closed. Pressure p_{56} initially increases and indicates forward shock motion (2), but the inlet unstarts (3) and causes pressure p_{56} to decrease because of the low pressure recovery (4). The spike is commanded to extend (5). As the spike extends, pressure recovery improves, as indicated by the increase in p_{56} (6). The spike extends until the inlet is restarted (7), and then the spike is commanded to return to its design point (8). The pressure recovery continues to increase, as shown by the increasing p_{56} , until the pressure reaches its operating point value (9). The restart cycle is completed when the spike reaches its design value.

A restart cycle with terminal-shock control is shown in figure 12. The points differing from those identified in connection with figure 11 are as follows. For this case

the pressure \bar{p}_{56} is used as the feedback signal in the terminal-shock control system. When the disturbance is applied, the control doors 1 and 5 attempt to compensate (10). The inlet unstarts, and the command pressure level to the control doors drops to its unstarted value (11) (dashed line in the \bar{p}_{56} trace) and causes the control doors to open (12) because the actual pressure exceeds the command pressure. After the inlet restarts, the command pressure exceeds the actual pressure, and the doors close rapidly (13). Oscillations are produced in the terminal-shock control system (14). These result because of the high gain of the terminal-shock control loop. To reduce these oscillations the controller gains should be reduced during the restart period. The oscillations are of the order of 30 hertz, which is the fundamental resonance of the inlet - long-duct combination. The control doors remain open during most of the unstart-restart cycle because of the nature of the command signal. When the inlet is coupled to an engine, the control doors will open as a function of spike position during the unstart-restart cycle.

SUMMARY OF RESULTS

A program was conducted on a mixed-compression inlet to develop a terminal-shock and restart control. The inlet was designed for operation at Mach 2.5 with a TF-30 engine. The experimental open-loop results were compared to transfer functions obtained from a curve fit program.

The controller form chosen for the terminal-shock control system was a proportional-plus-integral type because it results in zero steady-state error and desirable attenuation in the low-frequency range. The controller transfer function was obtained from a Lewis program that used experimental data and a cost function optimization program.

Closed-loop frequency responses of selected inlet diffuser static pressures used in the terminal-shock control system were presented. With the inlet coupled to the choked orifice the closed-loop response was below the open-loop response out to about 10 hertz and did not result in appreciable resonant amplitudes in the higher frequency range. However, with the inlet coupled to the long duct large resonant amplitudes occurred in the midfrequency range as the controller gains were increased to improve the low-frequency attenuation. For this inlet - long-duct combination the controller gains used must represent some tradeoff between the low-frequency attenuation desired and the acceptable resonant amplitude in the midfrequency range.

Inlet unstart-restart cycles with and without terminal-shock control were shown. The high controller gains required by the terminal-shock control system resulted in oscillations of the terminal-shock control loop. With the inlet coupled to an engine the

unstarted pressure comand should be made a function of spike position, and the terminal-shock controller gains should be reduced to prevent oscillations during restart.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 29, 1973,
501-24.

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TABLE I. - INLET AND TUNNEL TEST CONDITIONS

Tunnel free stream				Inlet	
Mach number	Total pressure, N/sq cm	Total temperature, K	Reynolds number per meter	Choked exit airflow, kg/sec	Termination
2.50	8.77	310	8 188 000	66.6	Choked plate
2.50	8.74	319	8 188 000	64.3	Long duct

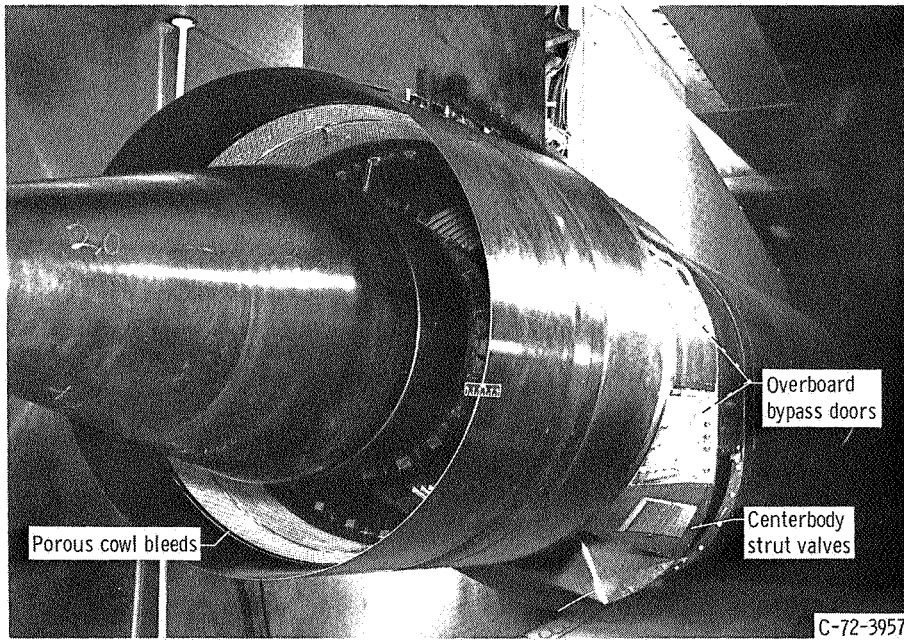


Figure 1. - Inlet installed in test section.

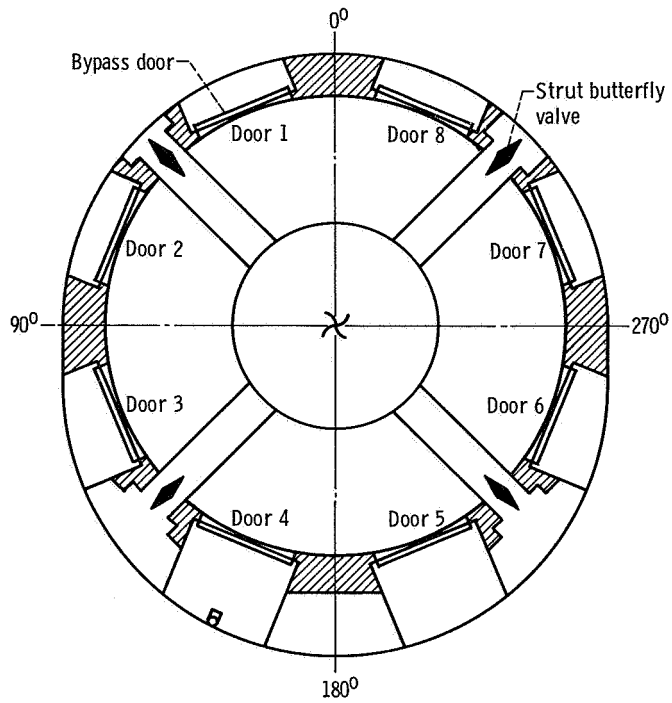


Figure 2. - View of inlet looking downstream showing bypass doors and centerbody bleed flow struts.

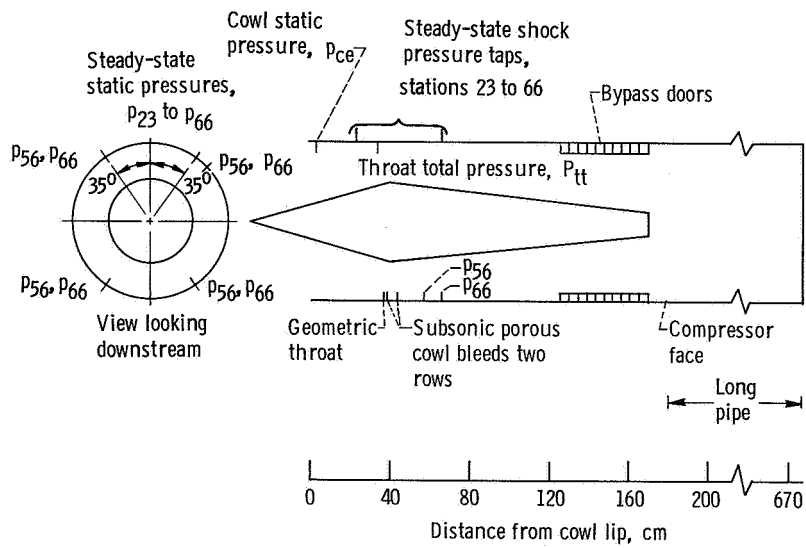


Figure 3. - Sketch showing location of steady-state and dynamic instrumentation on inlet.

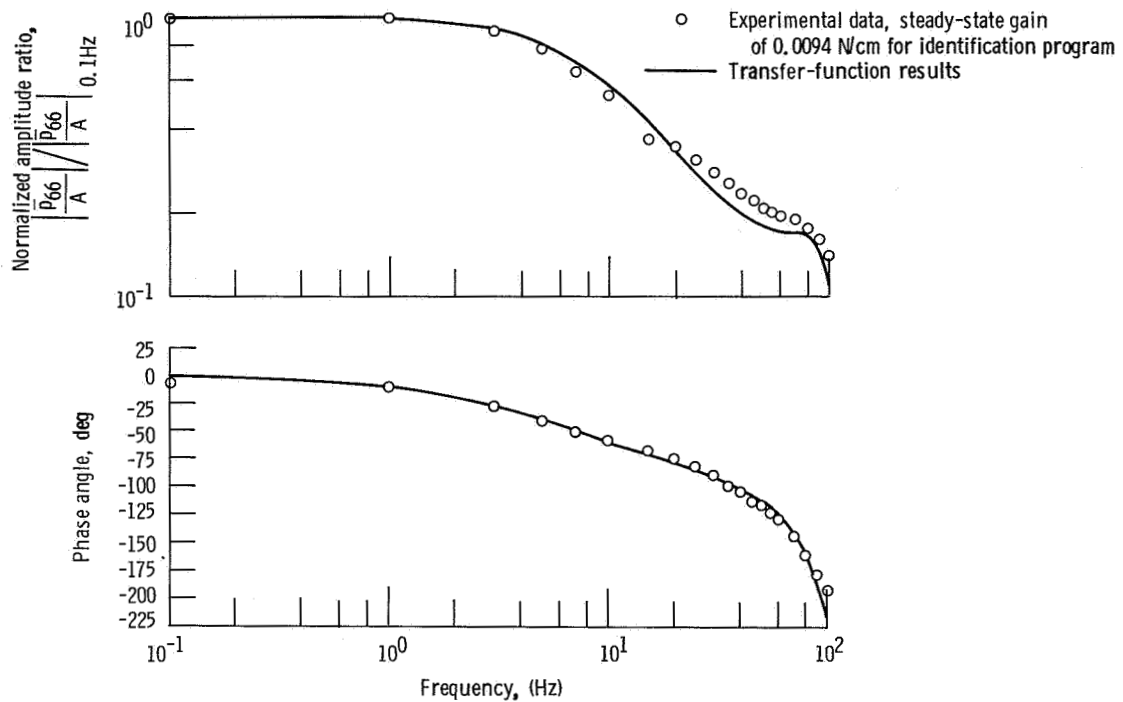


Figure 4 - Comparison of normalized frequency response of average static pressure at station 66.9 shown by results from transfer-function identification program and experimental test results. Mach number, 2.5; no cowl bleed; choked orifice termination; bypass doors 3 and 7 used for disturbance; transfer function,

$$\frac{\left| \frac{\bar{p}_{66}}{A} \right|}{\left| \frac{\bar{p}_{66}}{A} \right|_{0.1 \text{ Hz}}} = \frac{1}{\left[1 + \frac{s}{2\pi(6.67)} \right] \left\{ \left[\frac{s}{2\pi(89)} \right]^2 + \frac{2(0.247)s}{2\pi(89)} + 1 \right\} \left[1 + \frac{s}{2\pi(403)} \right]}$$

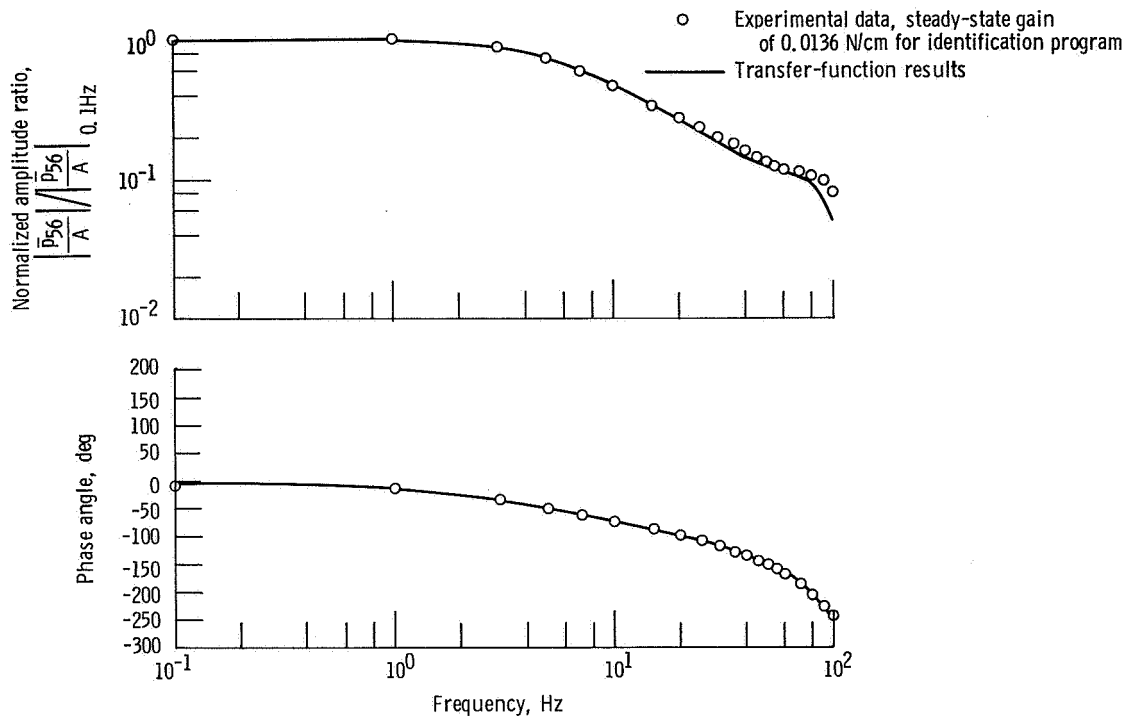


Figure 5. - Comparison of normalized frequency response of average static pressure at station 56.8 shown by results from transfer-function identification program and experimental test results. Mach number 2.5; no cowl bleed; choked orifice termination; bypass doors 3 and 7 used for disturbance; transfer function,

$$\frac{\left| \frac{\overline{p}_{56}}{A} \right|}{\left| \frac{\overline{p}_{56}}{A} \right|_{0.1 \text{ Hz}}} = \frac{1}{\left[1 + \frac{s}{2\pi(5.3)} \right] \left[1 + \frac{s}{2\pi(70.7)} \right] \left\{ \left[\frac{s}{2\pi(86)} \right]^2 + \frac{2(0.244)s}{2\pi(86)} + 1 \right\}}$$

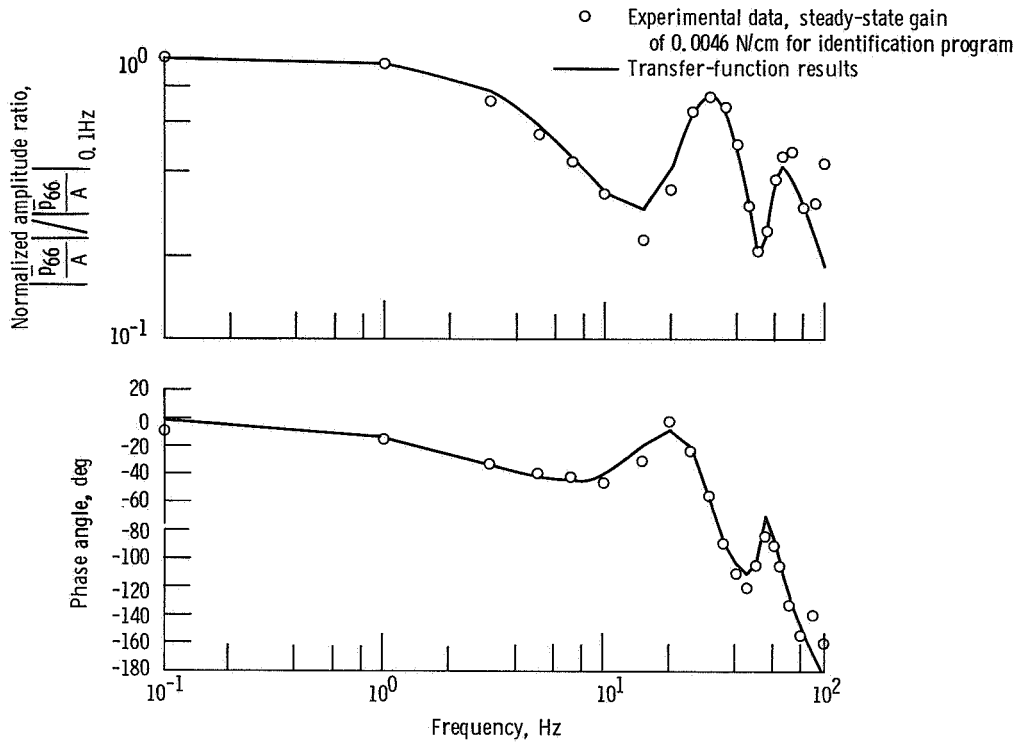


Figure 6. - Comparison of normalized frequency response of average static pressure at station 66, 9 shown by results from transfer-function identification program and experimental test results. Mach number, 2.5; cowl bleed; long duct termination; bypass doors 3 and 7 used for disturbance transfer function,

$$\left| \frac{\bar{p}_{66}}{A} \right| \bigg|_{0.1\text{Hz}} = \left\{ \left[\frac{s}{2\pi(15.6)} \right]^2 + \frac{2(0.447)s}{2\pi(15.6)} + 1 \right\} \left\{ \left[\frac{s}{2\pi(52.1)} \right]^2 + \frac{2(0.072)s}{2\pi(52.1)} + 1 \right\} \left[1 + \frac{s}{2\pi(3.7)} \right] \left\{ \left[\frac{s}{2\pi(57.6)} \right]^2 + \frac{2(0.139)s}{2\pi(57.6)} + 1 \right\} \left\{ \left[\frac{s}{2\pi(29.7)} \right]^2 + \frac{2(0.243)s}{2\pi(29.7)} + 1 \right\} \left\{ \left[\frac{s}{2\pi(93)} \right]^2 + \frac{2(0.46)s}{2\pi(93)} + 1 \right\}$$

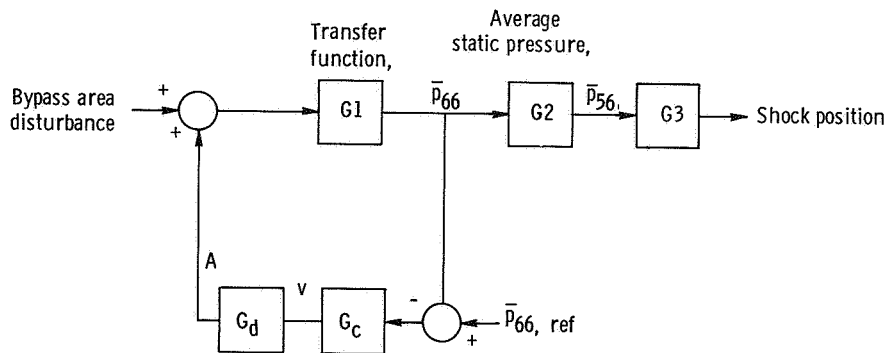
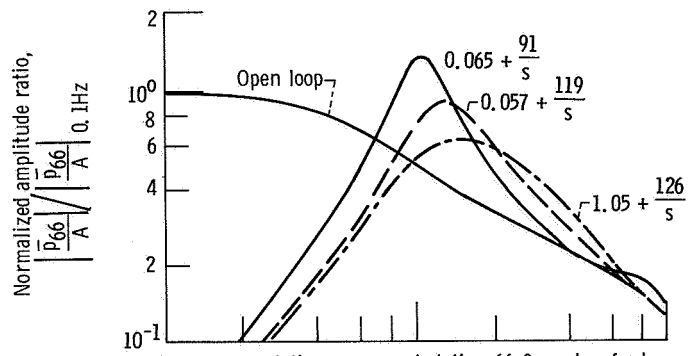
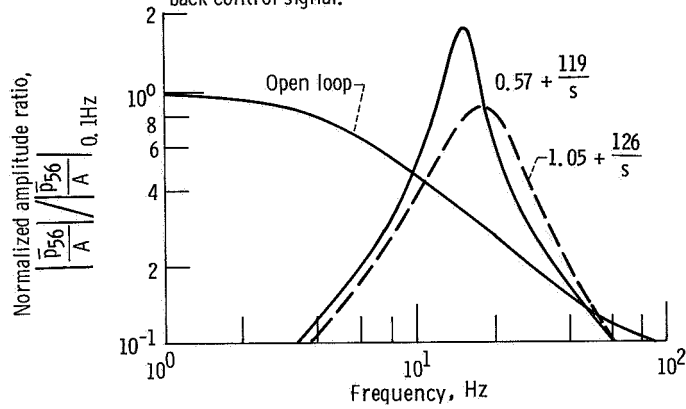


Figure 7. - Block diagram of inlet normal shock control system.



(a) Average static pressure at station 66.9 used as feedback control signal.



(b) Average static pressure at station 56.8 used as feedback control signal.

Figure 8. - Closed-loop responses of diffuser static pressures. Mach number, 2.5; no cowl bleed; choked orifice termination; bypass doors 1 and 5 used for disturbance; bypass doors 3 and 7 used for control.

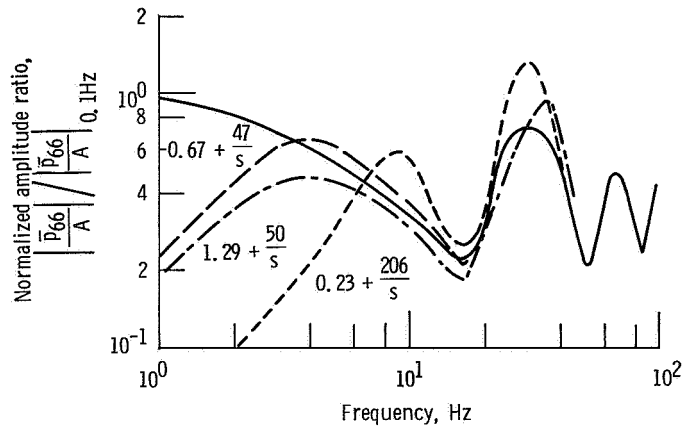


Figure 9. - Closed-loop response of average static pressure at station 66.9 (\bar{p}_{66}). Mach number, 2.5; cowl bleed; long duct termination; bypass doors 1 and 5 used for disturbance; bypass doors 3 and 7 used for control; \bar{p}_{66} used as control signal.

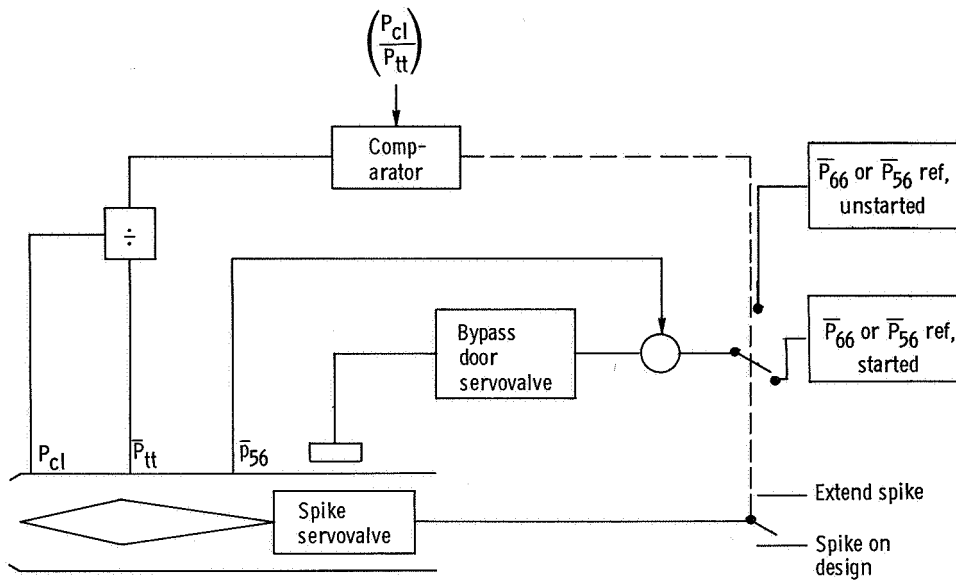


Figure 10. - Inlet restart control system.

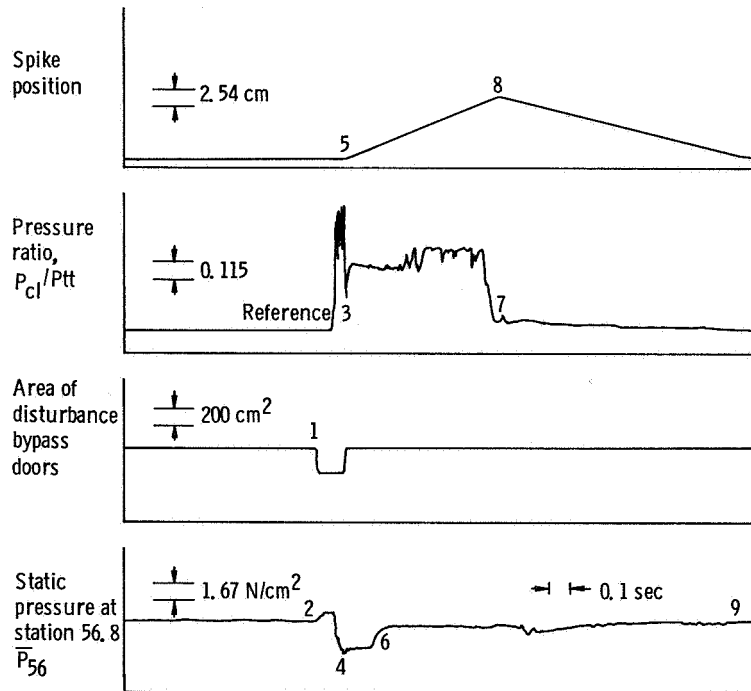


Figure 11. - Inlet restart cycle without normal shock control.

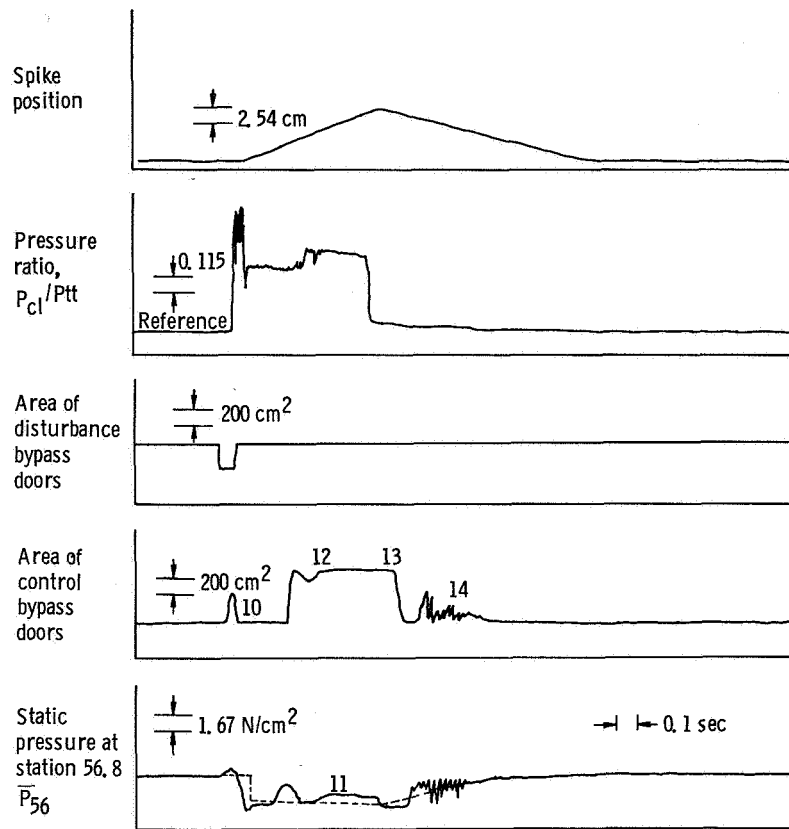


Figure 12 - Inlet restart cycle with normal shock control.