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EFFECT OF AFTERBURNER LIGHTS AND INLET UNSTARTS ON A MIXED-COMPRESSION-INLET TURBOFAN ENGINE OPERATING AT MACH 2.5

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16. Abstract

Data are presented to show the response of an uncontrolled inlet to afterburner lightoff disturbances when a mixed-compression inlet is coupled to a turbofan engine. The results show a significant upstream shock excursion when the afterburner lights which is a result of the direct communication between the afterburner region and the inlet by means of the fan duct and fan stages. In addition results of a waveform analysis on the inlet pressure response to the afterburner light is presented. Inlet unstarts and their effect on operation of the propulsion system is also discussed.

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SUMMARY

Data are presented to show the response of an uncontrolled inlet to afterburner light-off disturbances when a mixed-compression inlet is coupled to a turbofan engine. The results show a significant upstream shock excursion when the afterburner lights. The excursion is a result of the direct communication between the afterburner region and the inlet by means of the fan duct and fan stages.

The waveform of inlet pressure response to the afterburner light is analyzed to determine the frequency content of the response. Since the inlet pressure is indicative of shock position, the pressure transient indicates what the terminal shock is doing. The results are presented as a power spectral density and also as an explicit time function of the inlet pressure. The results show a strong low-frequency content of the time transient. Discrete frequencies at approximately 0.2 and 2 hertz appeared in the explicit time expression. With the inlet on control the maximum increase in airflow bypassed during an afterburner light is approximately 4.7 kilograms per second (corrected), which represents about 6 percent of the engine corrected airflow. In addition, the effect of inlet unstarts on the operation of the propulsion system is discussed, and results obtained with the turbofan engine are compared with results obtained from tests with a mixed-compression inlet - turbojet engine. The results show that the turbofan engine did not experience blowouts when the engine stalled. The engine did stall whenever the inlet unstarted.

SYMBOLS

A	area, m^2
p	static pressure, N/cm^2
P	total pressure, N/cm^2
T	total temperature, ^oC
t	time, sec
w_F	total fuel flow, kg/hr

Subscripts:

0	free stream
0.5	cowl lip
1	inlet throat
1.1	inlet diffuser
2	fan inlet
2.2	low compressor exit
3	high compressor exit
4	turbine inlet
5	low turbine discharge

INTRODUCTION

Knowledge of dynamic interaction between inlet and engine are important to the controls designer because the inlet control system has to compensate for disturbances due to these interactions. This knowledge is especially important because of the potential consequences resulting from either inlet or engine disturbances (unstarts, stalls, flame outs). Previous experience at Lewis was with a mixed-compression-inlet - turbojet combination. The results of that experience are presented in references 1 to 3.

This report presents results showing how afterburner light-offs (from a turbofan engine) affect inlet operation and also includes waveform analysis of the inlet open-loop pressure response for this inlet-engine combination resulting from an afterburner light. Data are also presented to show the effect of inlet unstarts on propulsion system performance.

A brief summary of the overall program is presented first. The model tested in the Lewis 3- by 3-meter (10- by 10-ft) supersonic wind tunnel was a mixed-compression inlet coupled to a turbofan engine. This was the first time that this combination was run supersonically. The major program objectives were to demonstrate that this combination could run successfully and that integration of the inlet and engine controls would allow the operation of the inlet without bypass flow (in steady state) by using the integrated controls to readjust the engine operating point. A detailed report on the results of the integrated controls program is presented in reference 4. A separate report on the shock control and restart control is presented in reference 5. This report will include some results not presented in these references. In addition selected figures appearing in reference 4 that deal with the large scale transient responses of the sytem are included. The purpose of presenting the analysis of the inlet pressure resulting from an afterburner light is to identify the frequency content of the disturbance to aid the control designer in choosing sufficient control door bandwidth for the shock control system. In previous tests (ref. 1) fast response bypass doors were used for terminal shock control against downstream disturbances with the inlet coupled to turbojet engines. With the waveform analysis in this report some information is available on the type of disturbances produced by a turbofan engine.

The results are presented in the following order: Transients showing how inlet-engine variables respond to afterburner lightoffs when there is no terminal shock control. Next, the waveform analysis of this inlet open-loop pressure response produced by the afterburner light is presented. Finally, inlet unstart transients are shown and their effect on propulsion system operation is discussed.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

Tests were conducted in the 3- by 3-meter (10- by 10-ft) supersonic wind tunnel. The propulsion system tested was a mixed-compression-inlet - turbofan engine combination. Figure 1 shows the system installed in the wind tunnel.

Inlet

The axisymmetric, mixed-compression inlet (fig. 2) with translating centerbody has an approximately 45-percent internal supersonic area contraction at the design Mach number. The inlet was designed for Mach 2.5 operation with a TF-30 engine. The inlet has a capture area of 0.707 square meter and measures 180 centimeters from the cowl lip to the fan face. A report on the inlet design and performance is presented in reference 6.

Provisions were made for boundary-layer bleed on the centerbody and cowl. For this program the inlet was tested with the cowl bleeds blocked. The centerbody has is a slot type bleed. The centerbody bleed flow was ducted to four equally spaced struts located in the diffuser section. Centerbody bleed flow was controlled by a butterfly valve in each strut. Figure 3 is a sketch of the diffuser showing the butterfly valves. The butterfly valves were positioned by electrohydraulic servos using rotary hydraulic actuators. The strut valves were used to produce inlet unstarts by momentarily closing them, which resulted in the choking of the inlet throat. A small amount of centerbody bleed was required to keep the inlet started. The strut valves were also used to provide additional inlet stability during afterburner disturbances when the slow bypass doors were used for shock position control. A detailed account of how this was accomplished is presented in reference 4.

The inlet is equipped with eight slotted, sliding-plate overboard bypass doors used to match inlet-engine airflow. Figure 3 also shows the circumferential location of the bypass doors. The even numbered doors were used for disturbance, and the odd numbered doors were used by the terminal shock control system. The total area of the four control doors was 0.161 square meter, and the total area of the four disturbance doors was 0.02 square meter. The control bypass doors operated from the error signal generated by measuring an inlet pressure (which was indicative of terminal shock position) and comparing it with a command value. The error was modified by a proportional-plus-integral filter and moved the control bypass doors in a direction to reduce the error to zero.

Inlet Instrumentation

Figure 4 is a sketch of the inlet showing the pressure instrumentation locations in terms of inlet station numbers. Steady-state pressure instrumentation was used to measure the terminal shock position. These 16 steady-state transducers start 23 centimeters from the cowl lip and extend to a point 66 centimeters from the cowl lip. The 14 transducers farthest upstream are 2.54 centimeters apart with the last two 5.08 centimeters apart. These steady-state measurements were used to set the shock at its operating point.

The transient pressures were measured with strain-gage transducers connected to the cowl with short tubes. As shown in figure 4, there is a plane containing dynamic pressure transducers located 66 centimeters from the cowl lip (station 1.1). The four transducers in this plane, spaced 90° apart, were electrically averaged. The average pressure is identified as $p_{1.1}$. In addition to these transducers, others were used to measure the total pressure at the inlet's geometric throat (P_1) and the static pressure on the cowl near the lip ($p_{0.5}$). The ratio $p_{0.5}/P_1$ was used as the inlet unstart sensor.

Engine

The engine used in this investigation was a Pratt & Whitney TF-30 P-3. The TF-30 is an axial, mixed-flow, augmented, twin spool, low-bypass-ratio turbofan engine with a variable area convergent primary nozzle. A schematic of the engine is shown in figure 5. The engine stations are shown in this figure. (A more detailed description of the engine and its control system are presented in ref. 4 and will not be included here.) All engine pressure signals were sensed by strain-gage pressure transducers and were obtained by tapping off of the pressure tubes going to the main fuel control. The high-pressure turbine-inlet temperature T_4 is the manufacturer's signal, which is based on the temperature rise across the compressors and the low-pressure turbine-discharge temperature. Fuel flows were measured by turbine flowmeters.

Test Conditions and Procedures

All tests were conducted at the following average free-stream conditions: Mach number, 2.5; total temperature, 297 K; total pressure, 9.3 newtons per square centimeter; Reynolds number, 8.2 million per meter; and specific-heat ratio, 1.4. The propulsion system was operated at zero angle of attack during all the tests. Disturbances were produced by lighting the afterburner or unstarting the inlet (by momentarily closing the bleed valves). Steady-state data were recorded on the Lewis data system, and transient data were recorded on two eight-channel strip chart recorders and on magnetic tape.

RESULTS AND DISCUSSION

Afterburner Transients

In a turbofan engine there is a direct path of communication between the afterburner and the inlet. Any disturbance, such as an afterburner light or cutoff, will affect inlet stability. The light off results in an increase in temperature resulting in decreased mass flow (density decreases). The sudden reduction in mass flow produces an increase in pressure. The pressure disturbance propagates upstream through the fan duct and results in an increased pressure ratio across the fan causing a subsequent flow reduction through the fan. The reduced flow requirements of the engine cause the shock to move upstream of its operating point toward the unstarted condition. If the flow disturbance is of sufficient magnitude, the inlet will unstart. The unstart produces a sharp reduction in pressure recovery at the compressor face and an increase in distortion that may result in an engine stall. Although no data are presented for afterburner cutoffs, one might expect the shock to be pulled more supercritical and to result in higher distortion levels which also may result in an engine stall.

Figure 6 illustrates how the inlet responds to an afterburner light for this particular inlet/engine combination. Also shown are engine variables as they respond to the disturbance. For the case shown in figure 6 there is no shock control. The engine control system was operating normally, however. The shock operating point was set 21 centimeters downstream of the normal operating point to avoid unstarting the inlet. The total-pressure recovery at this operating point was approximately 85 percent. Normally, the recovery is 89 percent with the shock at the operating point, which was approximately 40 centimeters from the cowl lip.

The afterburner light is detected by noting the sharp rise in low-pressure turbine-discharge pressure P_5 (fig. 6, point a) The inlet pressure $p_{1.1}$ (b), which is indicative of shock position, increases indicating upstream motion of the shock. The pressure disturbance generated by the light off also enters the main core of the engine through the splitter plate separating the fan from the compressor. The pressure pulses in the main core are seen at the discharge of the low compressor $p_{2.2}$ and the high compressor p_3 (c). Other effects of the lightoff on the engine that are not shown were a slight reduction in low rotor speed and an increase in turbine-inlet temperature during the transient. The speed was affected by the increase in temperature at the turbine discharge because the work extracted by the turbine was reduced. The T_4 increase was caused by the pressure pulse appearing at the high compressor because fuel flow is a function of p_3. The lightoff caused the shock to move from its operating point to near the unstart point. If no other action is taken, the shock would stay at this point because of the new flow balance. However, the exhaust nozzle opens (point d) to compensate for the reduced effective flow area created by the light off, and the shock returns to its prelight point.

An analysis of the pressure waveform resulting from an afterburner light with no inlet control is presented next. Knowledge of the characteristics of the inlet pressure response to an afterburner light can be of value to the controls engineer to help determine the bandwidth of the control doors required for this type of disturbance. Pressures $p_{1.1}$ and P_5 in figure 6 were not recorded on tape; the only record was a strip chart recording. Thus, the results presented in this section were obtained by scaling the time transient data for the $p_{1.1}$ and P_5 plots of figure 6. Although some loss of accuracy resulted, the main characteristics of the disturbance were preserved. The scaled data were used as input data to a fast Fourier transform (FFT) program to obtain the power spectral density (PSD) of the signals. This was done to determine the frequency content of the signals.

Figure 7 shows the PSD's obtained using the $p_{1.1}$ and P_5 data of figure 6. The results show that the frequency content of the signals is limited to the range below 3 hertz. However, it should be noted again that the higher frequency terms that might be available in the actual signal were probably filtered out by the method used in extracting the data from the strip chart because, as shown in figure 6, the $p_{1.1}$ signal does not return to its preafterburning point but oscillates. The low-frequency content is a function of the record length of the data. Some error in the low-frequency region may be due to the method used to truncate the data.

Another method of analysis of the $p_{1.1}$ and P_5 data shown in figure 6 was used to attempt to identify the frequency content of the inlet pressure trace. The pressure-time data scaled from figure 6 was used as input to a complex curve fit routine to obtain an explicit time expression of the signal:

$$p_{1.1}(t) = 5.782 \exp(-1.1918\, t) \cos(0.9992\, t - 1.3904) + 1.15 \exp(-3.2021\, t) \cos(13.94\, t - 3.75)$$

The expression shows that there are dominant frequencies at approximately 0.2 and 2 hertz. Figure 8 shows both the actual data obtained from the strip chart and the approximation based on the expression. It compares reasonably well with the $p_{1.1}$ trace.

Figure 9 shows an afterburner light with inlet control using the 80-hertz doors with the shock at its normal operating point. From this figure an estimate of the peak flow rejected by the engine as a result of the afterburner light can be obtained. Since the bypass doors are choked, the flow bypassed is proportional to the change in door area (ignoring the pressure effect). The maximum flow bypassed is approximately 4.7 kilograms per second (corrected). The engine corrected airflow is approximately 70 kilograms per second. The peak bypass flow during the transient is approximately 6 percent of the engine flow. The events recorded in this figure are similar to those discussed for figure 6 with the exceptions that there is inlet control and that the shock is at its normal operating point.

Unstart-Restart Transients

Inlet unstarts can be caused by changes in flight Mach number or produced by afterburner lights, etc. Unstart transients and their effect are discussed in this section. For the first results shown, the inlet was intentionally unstarted by momentarily closing the centerbody bleed valves, which resulted in choking of the inlet throat and subsequent unstart. For this type of disturbance the control bypass doors would not be effective in preventing an unstart. When the inlet unstarts, pressure recovery at the compressor face drops, and distortion levels increase causing the engine compressor to stall.

Figure 10 shows time traces of inlet-engine variables for an inlet unstart-restart cycle. A proportional-plus-integral control was used for terminal shock control and an automatic restart feature was provided. (See ref. 5 for details on the shock control and restart control.) Closing the centerbody bleed valves momentarily initiates the unstart. The inlet unstarts (point a) as indicated by the cowl static- to throat total-pressure ratio ($p_{0.5}/P_1$). The unstart results in a drop in pressure recovery as noted by the P_2 trace (b). Inlet restart action is initiated. A complex function of spike position was used as the controller shock position command signal during the restart cycle (c). This function insures that the inlet will not go into buzz. The spike is commanded to extend (d). Restart occurs when the proper capture flow to throat flow ratio is achieved and the spike is commanded to return to its operating point (e). The reduced pressure (caused by the unstart) at the compressor face causes the engine to stall. A large hammershock is noted in the inlet ($p_{1.1}$ trace) and is also detectable on the low pressure discharge trace ($p_{2.2}$; fig. 10, point f). Stall recovery is completed during the inlet restart cycle. The engine control reduces fuel flow (g) to prevent excessive turbine inlet temperature.

Figure 11 shows an inlet unstart produced by an internal disturbance, namely, an afterburner light. These data were taken with an active coupled control (see ref. 4) and with slowed up bypass doors. For the data shown the unstart produced by the afterburner lightoff shows different characteristics compared to the unstart produced by the upstream disturbance (fig. 10). The afterburner light (a) causes the terminal shock to move upstream (b). Before the control can act the shock is expelled, resulting in an inlet unstart (c) and an engine stall with a more noticeable hammershock occurring on the $p_{2.2}$ trace but not evident on the inlet pressure trace $p_{1.1}$ (d). With the onset of the disturbance, the coupled engine control could not respond fast enough in the transient sense, and the bypass doors attempt to compensate by opening (e). A second engine stall occurs in this case with large pressure hammershocks occurring in the engine and inlet (f). The second stall occurs at the restart point, but the engine recovers and returns to its operating point.

The reason for the second stall occurring at the restart point may be that at the restart point the distortion is highest. The total fuel flow increases before the lightoff because the flowmeter measuring fuel flow was located upstream of the spray nozzle manifold. The fuel flow trace (fig. 11, point g) indicates the additional amount of fuel required to fill the fuel manifold. The integrated control was active for this test and the bypass doors closed again after the transient ended (h).

The second stall that occurred, as shown in figure 11, seemed to occur with either the slowed down doors or 80-hertz bypass doors but did not occur consistently. However, when the second stall occurred, a large pressure hammershock was noted in the inlet. No engine blowouts were encountered when the inlet unstarted but the engine did stall but recovered from the stall.

In reference 3 it is mentioned that stalls did not always occur for the turbojet engine at Mach numbers lower than 2.5 but that, when the engine did stall because of an unstart, there almost always was a combustor blowout. However, in the case with the turbofan engine, stalls always resulted when the inlet was unstarted, but at no time did the combustor blowout. Both of these engines were run at the same ambient temperatures at Mach 2.5.

SUMMARY OF RESULTS

The results presented herein show that significant upstream shock excursions occur when the afterburner lights and point out the need for terminal shock control. The afterburner disturbance enters the inlet through the engine's fan duct and fan stages. The shock control required for this type of disturbance must provide sufficient attenuation in the low frequency region and must be fast enough to react satisfactorily to the disturbance. Analysis of the inlet pressure response to the afterburner light showed strong low-frequency content, and the explicit time function obtained indicated that the pressure function had strong content at approximately 0.2 and 2 hertz.

Inlet unstarts resulted in engine stalls, but the engine always recovered by itself. Other data considered, but not shown, indicate that there is no correlation of inlet hammershock occurrence or of double stalls with the method used to initiate the unstart-stall phenomena (e.g., upstream or downstream disturbance). However, in those cases where the second stall occurred, a hammershock wave was noticed on the inlet pressure trace. The second stall usually occurred at the inlet restart point. The second stall may be caused by the high distortion level at the restart point. At no time during the unstart tests did the engine experience a blowout. But, in previous tests with a turbojet engine, blowouts were common when the inlet unstarted and engine stalled. In addition there were instances when the turbojet engine did not stall when the inlet unstarted, but this was not the case with the turbofan engine which stalled whenever the inlet unstarted.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 30, 1975,
505-05.

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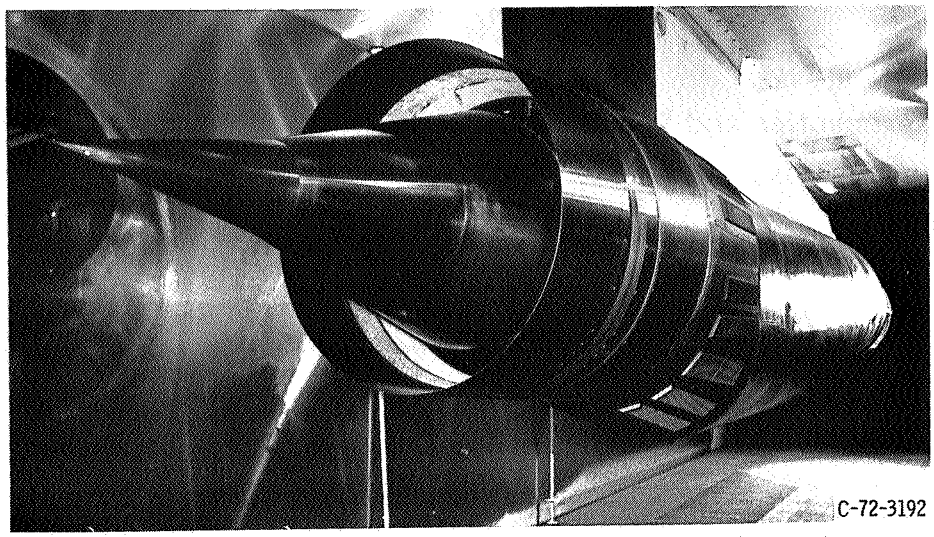

Figure 1. - Axisymmetric inlet and TF-30 P-3 nacelle.

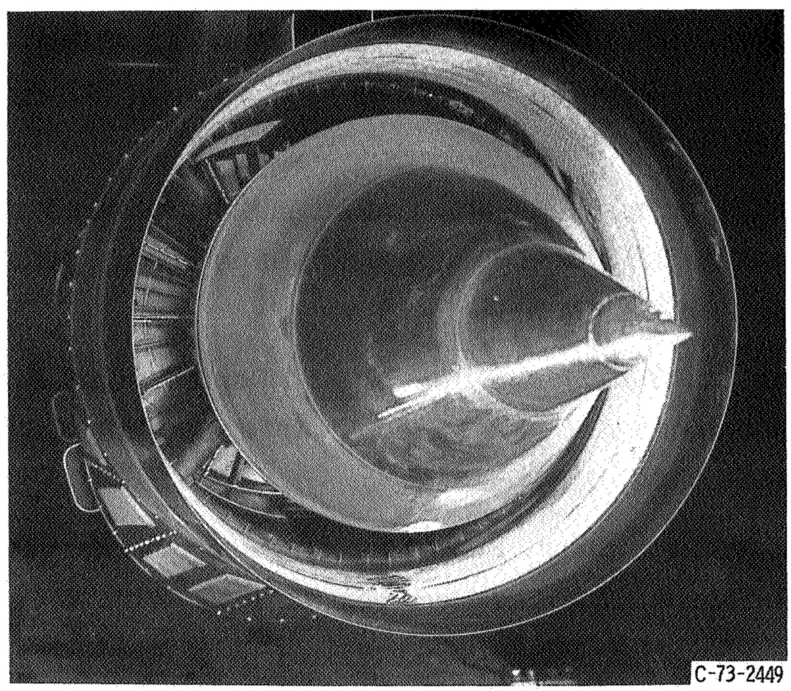

Figure 2. - Inlet and TF-30 P-3 fan.

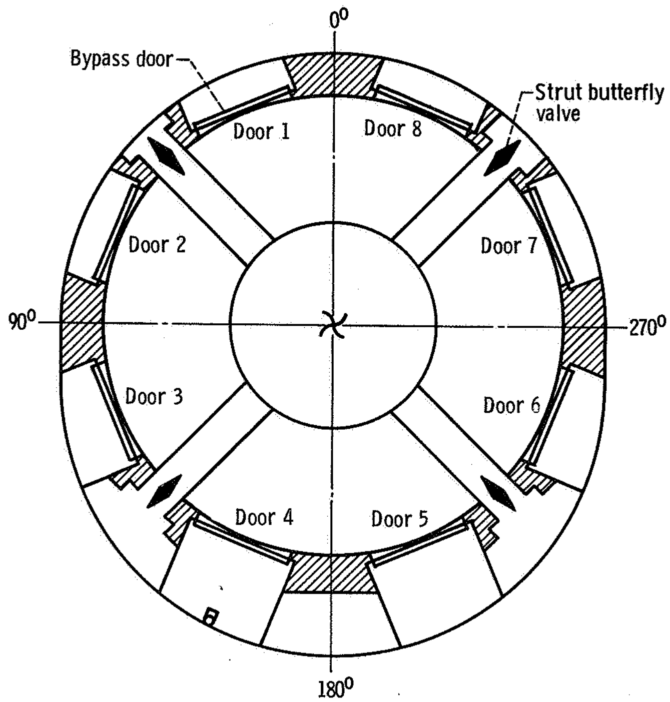

Figure 3. - View of inlet looking downstream showing bypass doors and centerbody bleed flow struts.

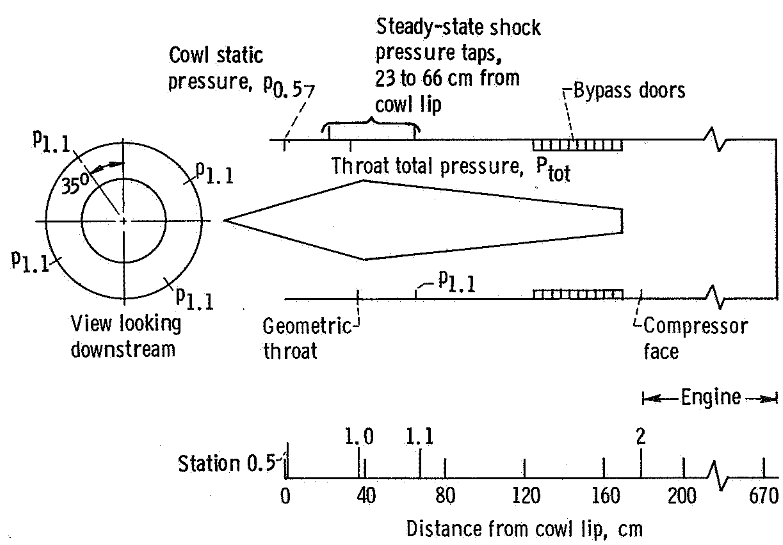

Figure 4. - Location of steady-state and dynamic instrumentation and station numbers on inlet.

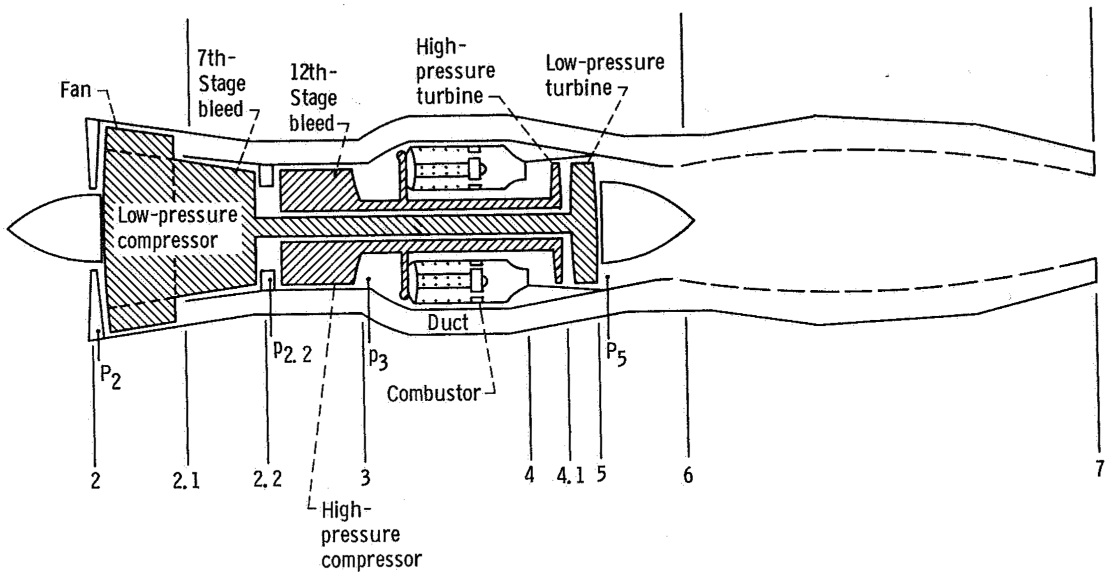

Figure 5. - Engine stations and instrumentation locations.

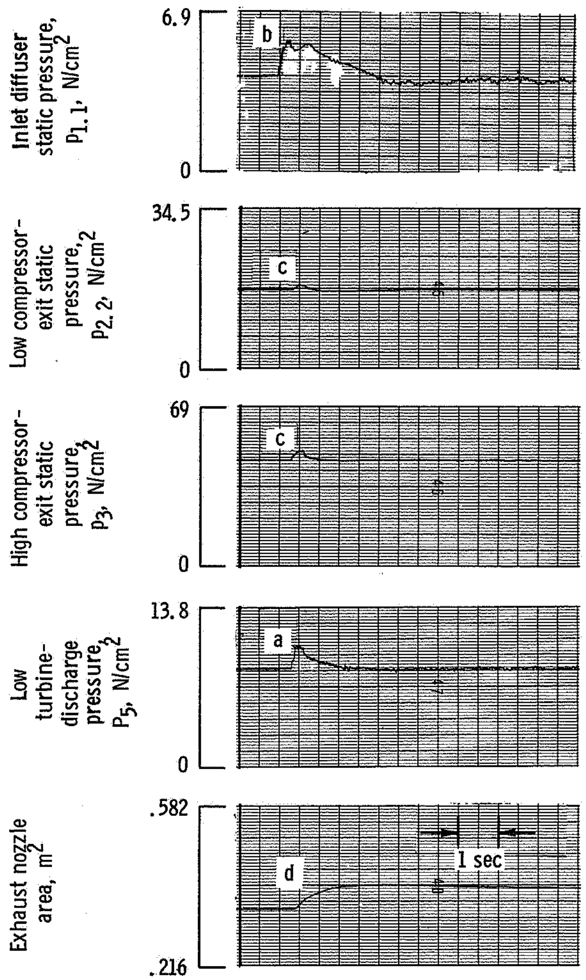

Figure 6. - Afterburner lightoff transient without inlet terminal shock control.

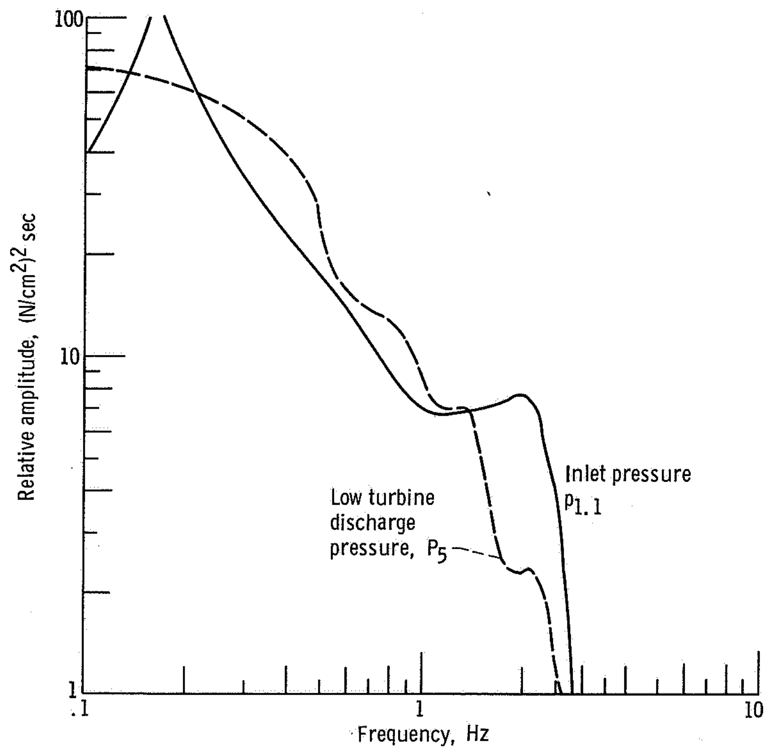

Figure 7. - Relative power spectral densities of low turbine discharge pressure and inlet pressure.

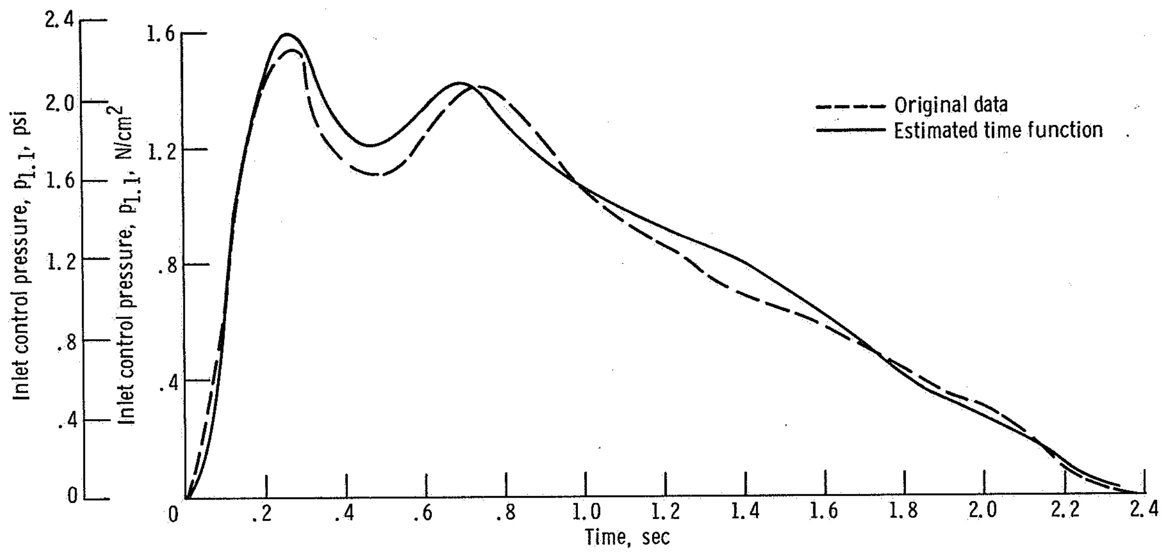

Figure 8. - Comparison of scaled $p_{1.1}$ signal with explicit time function obtained from curve fit estimate.

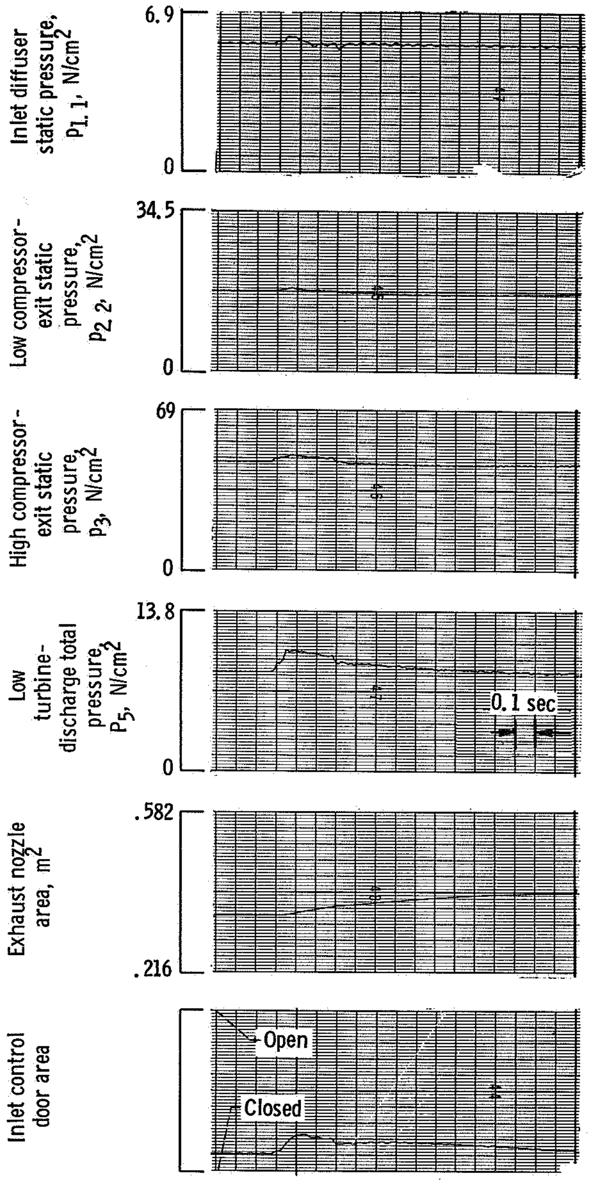

Figure 9. - Afterburner lightoff with inlet on control using fast bypass doors for shock control.

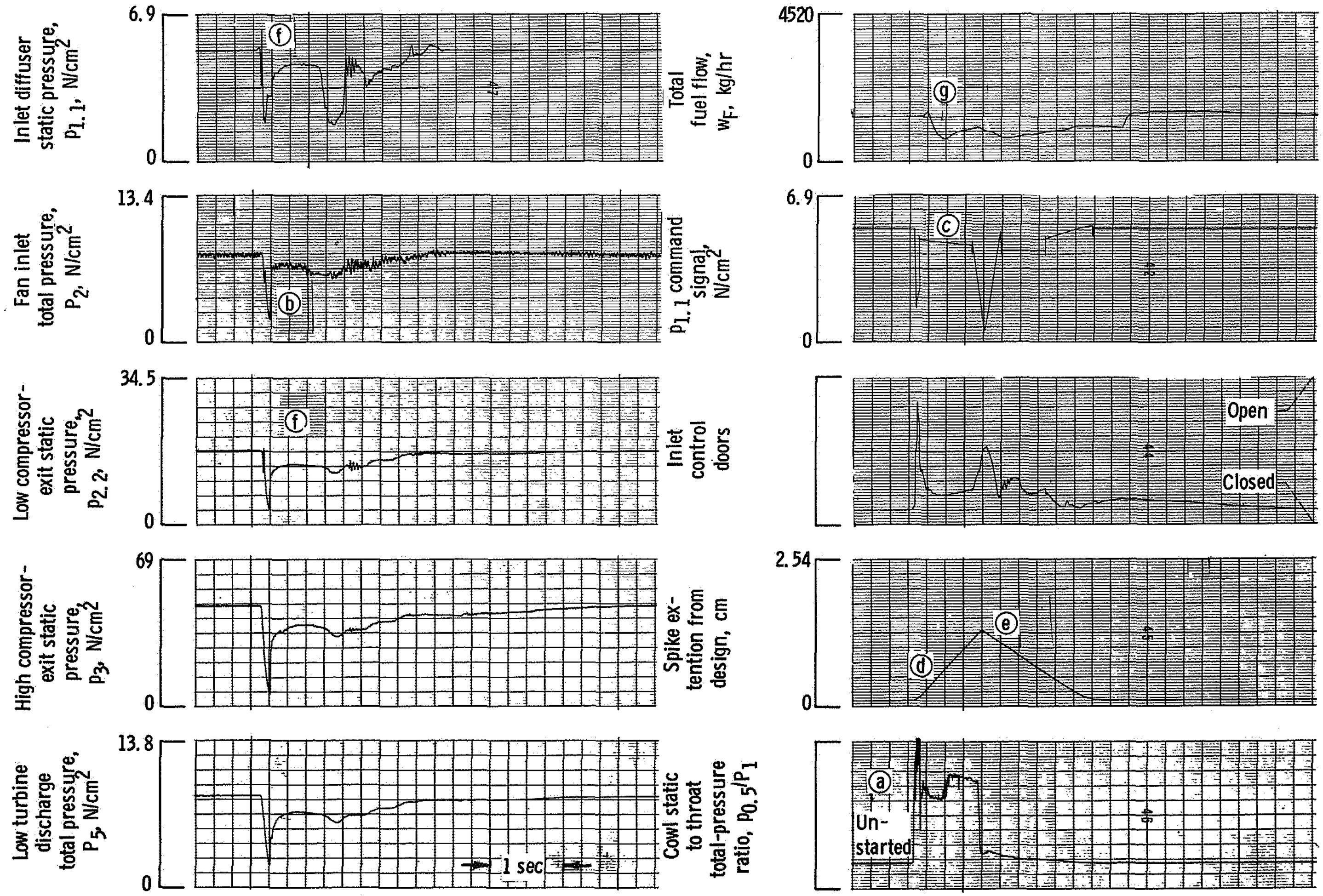

Figure 10. - Inlet unstart using strut valves to unstart (nonafterburning).

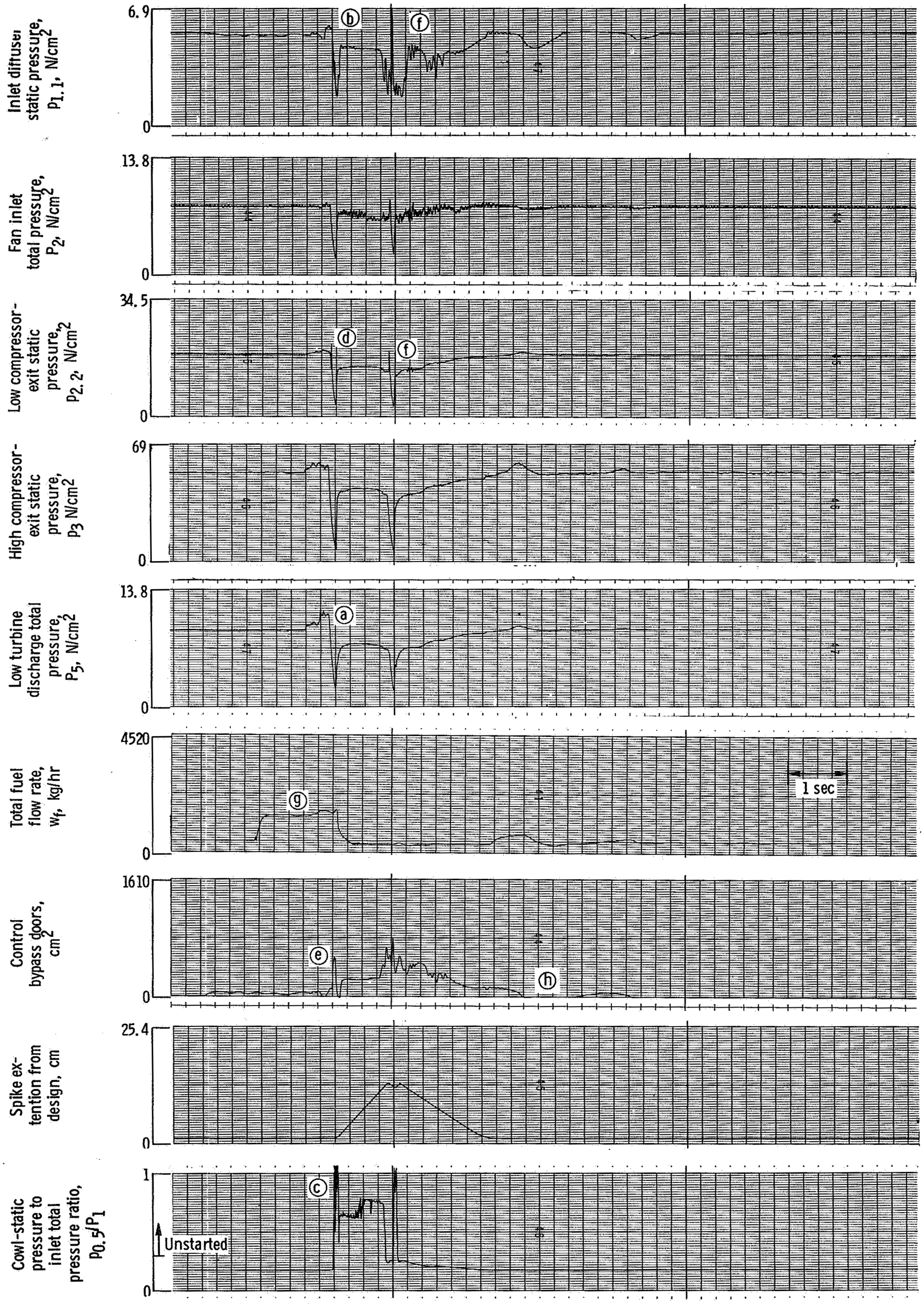

Figure 11. - Inlet unstart induced by afterburner light with slow inlet control doors.