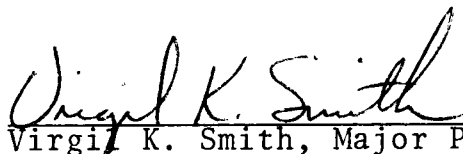
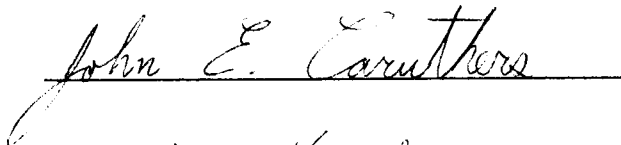
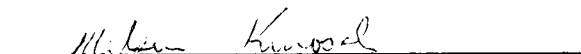


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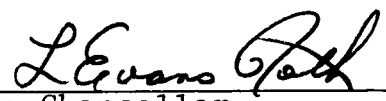
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EVALUATION OF AN AIRJET DISTORTION GENERATOR USED TO
PRODUCE INLET TOTAL-PRESSURE DISTORTION
FOR TURBINE ENGINE TESTING

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jerry Dean Hubble
March 1979

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ABSTRACT

The inflexibility of distortion screens in the testing of gas turbine engines has dictated the need for a quicker, more flexible method of producing inlet total-pressure distortion. In response to this need a performance evaluation of an airjet distortion generator system, used to produce steady-state total-pressure distortion at the inlet to a turbine engine, was conducted.

The capability of the system to duplicate screen-generated patterns and to maintain a constant distortion pattern over a range of airflows is presented. The effect of Reynolds number on the system's capability to match patterns is also investigated. A comparison of the effects of inlet distortion produced by screens to that produced by the airjet distortion generator system on the stability characteristics of the General Electric F101-GE-100 turbofan engine is described.

The major findings of this investigation were that the airjet distortion generator system could produce inlet distortion patterns within the error normally obtained by screens, and that the engine stability characteristics differed little with the two distortion methods.

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CHAPTER I

INTRODUCTION

The recent increase of emphasis on the effects of inlet total-pressure distortion on turbine engine stability and performance has resulted in a major effort at ground test facilities to improve the simulation of the total-pressure profiles at the compressor/fan face encountered during operation of engines over the aircraft flight envelope. An engine compressor will encounter a variety of distortion patterns over a wide range of engine airflow rates, inlet configurations, and aircraft angles of attack and sideslip. To adequately define the engine stability characteristics, testing with a large number of unique distortion patterns is required. The most widely accepted approach for producing the distortion patterns has been the use of complex assemblies of various porosity screens. The inherent inflexibility of the screen configuration (single design operating point) and the extensive developmental effort required for each screen dictated the need for a more flexible, economical, and timely method of producing total-pressure distortion. In response to this need, an effort to provide an alternate method to distortion screens

has been in progress at the Arnold Engineering Development Center (AEDC) during recent years [1 and 2].¹

The airjet distortion generator (ADG) system provides a method for producing steady-state, total-pressure spatial variations at the inlet of turbine engines. This system employs the principle of canceling momentum in the engine inlet primary airstream by the injection of counter-flowing secondary air, thus effecting a change in total pressure. The equipment consists of a matrix of counter-flowing airjets upstream of the engine face. A variety of engine inlet total-pressure patterns and distortion levels can be remotely set by controlling the secondary flow rate and distribution of airflow through this system of counter-flowing jets. A digital computer control system controls the airflow rate through each jet and makes the airjet system an efficient tool for setting a wide range of inlet distortion patterns in a timely manner.

1.1 Previous Investigations

Because of the inflexibility of the screen method of producing total-pressure distortion for engine testing, an effort to provide an alternate method using an airjet distortion generator has been investigated through various programs at the AEDC and other test facilities. These

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

investigations have included feasibility tests, investigations of an airjet in conjunction with an engine simulator, and finally, investigations of an airjet distortion generator system in conjunction with an operating turbine engine.

The development of the ADG at the AEDC began in 1970 with the investigation of a prototype ADG system during a turbofan engine test program [1]. Although this system could only produce distortion in one 45-degree segment of the engine face, the results obtained during this program indicated that the concept was potentially an alternative to the varying porosity screens for producing total-pressure distortion patterns at the face of gas turbine engines.

Other investigations into the concept of counter-flowing airjet to create low total-pressure regions also concluded that the concept was feasible [3 and 4]. In 1970 an investigation was conducted at NASA's Lewis Research Center using the airjet concept to distort the total-pressure profile in an airflow duct [3]. The airjet array contained 54 secondary-flow nozzles uniformly distributed over the duct cross section, but secondary-flow could only be controlled in groups of nine nozzles in 60-degree sections. It was concluded that this technique provided a convenient and acceptable method to produce steady-state, total-pressure profiles.

An investigation of combustor inlet distortion by Allison Division, GMC in 1971 used a 44-jet array to study the secondary-flow concept [4]. The jets had the capability to inject secondary air both with and counter to the primary flow. It was concluded that the counter-flowing jets could produce the desired total-pressure distortion, but the injection of secondary airflow in the direction of the primary flow produced abrupt increases in total-pressure that were not acceptable.

In 1972 a functional and structural investigation of an airjet distortion generator was conducted at the AEDC using an engine simulator [1]. The primary objective of this program was to demonstrate the flexibility of the ADG system and to compare the performance of the system with that of conventional inlet distortion screens. A secondary objective was to evaluate the performance of a high-response, total-pressure instrumentation system suitable for use in full-scale engine testing. The front face of the engine simulator was fully instrumented with 48 dynamic and 48 steady-state, total-pressure probes located on eight rakes with six probes per rake. Control of the 56 airjets for this program was completely manual.

Results from this program showed that the presence of the airjet strut assembly had no detectable steady-state or dynamic effect on the flow field at the simulator face. The high-response, total-pressure instrumentation indicated that turbulence would not be significant with the ADG

system, with a maximum measured turbulence level of 1.6 percent. It was concluded from this program that the ADG system could provide an acceptable means for generating total-pressure distortion over the range of inlet Mach numbers usually experienced in engine testing.

The next program, conducted in 1975-76, investigated the total ADG system capability using a typical turbofan engine in a normal engine test environment [2]. Specifically, the test objectives were to assess the fidelity of total-pressure distortion patterns produced by the ADG system, to demonstrate the capability of the ADG system to maintain a total-pressure distortion pattern over a range of engine airflow rates, and to compare the effects of distortion produced by the ADG system to the effects of screen-generated distortion on the stability characteristics of a turbofan engine.

The engine front face was instrumented with 48 steady-state total pressure probes located on eight rakes with six probes per rake. However, because the previous program indicated there was essentially no significant turbulence produced by the ADG system, only two dynamic, total-pressure transducers were used.

During this test program the 56 individual airjet valves were controlled by a digital computer. Total-pressure was measured at the engine face at 48 locations, and each measurement was compared to the value needed at that location to achieve the desired overall pattern. From

this comparison the individual airjet valves were commanded to either open or close until the desired total pressure level was achieved at each location, giving the desired overall pattern.

Results obtained during this program indicated that, for the limited number of total-pressure distortion patterns attempted, the ADG system was capable of reproducing the screen-generated patterns with acceptable fidelity. The ADG system pattern was also shown to be nearly constant over a range of engine airflow. However, the ADG system patterns resulted in engine component surge occurring at lower pressure ratios than for screen-generated patterns. During this program limited turbulence measurements indicated values as high as 6 percent, and it was concluded that this was the cause for the differences in component surge pressure ratios for distortion patterns produced by the two methods.

I.2 Purpose of the Present Investigation

The 1972 and 1975-76 programs resulted in a contradiction in regard to the turbulence level in the flow field downstream of the ADG system. To resolve this contradiction, to better understand the differences in engine component stability noted in the previous investigation, and to evaluate the fidelity of total-pressure distortion patterns produced by the ADG system over a wide range of

patterns required additional testing. A test program to resolve these issues should include investigation of the ADG system in conjunction with a state-of-the-art turbofan engine which is fully instrumented for both steady-state and dynamic total-pressure measurements, followed by an in-depth analysis of the inlet flow field turbulence and component stability as shown by surge pressure ratio.

A test program utilizing a General Electric F101 turbofan engine in conjunction with an airjet distortion generator system was conducted in 1977-78 at the AEDC. This investigation included tests to determine if the ADG system is a viable candidate to replace varying porosity screen overlays for inlet pressure distortion testing of turbojet and turbofan engines. The scope of the investigation not only included the assessment of the fidelity with which the ADG could produce a desired parametric, total-pressure pattern, but also provided (1) a direct comparison of F101-GE-100 turbofan engine surge characteristics with distortion patterns generated by both screens and the ADG; (2) engine surge characteristics with selected composite patterns simulated with the ADG and compared to historical screen data; and (3) a documentation of the effect of Reynolds number on the surge characteristics with inlet distortion patterns set by the ADG.

The investigation included an analysis of steady-state and dynamic, total-pressure measurements made at the engine face, with distortion being produced by both the ADG

system and distortion screens. Also included was an analysis of engine component stability with distortion being produced by both distortion methods. As a result of the analysis, conclusions were drawn regarding the effectiveness and performance of the ADG system, and recommendations for further investigations were made. The following describes the tests and results.

CHAPTER II

DATA ACQUISITION

The evaluation of the performance of the ADG system required the acquisition of data describing the inlet pattern and engine component response resulting from both screen distortion and ADG system operation. Steady-state, transient, and high-frequency total-pressure measurements were made at the engine face to determine both the steady-state and dynamic characteristics of distortion patterns. Engine component rotational speeds, pressure ratios, and airflow rates were measured.

II.1 Apparatus

II.1.1 Test Article

The airjet distortion generator (ADG) (Figure 1, Appendix A)² consists of three basic systems: a high-pressure air control and temperature-conditioning module, airjet rake spool assembly, and the distortion pattern digital computer control system. The pressure sensor probes for the computer inputs for pattern control were located in the front frame of the F101-GE-100 engine (Figure 2). Airjet distortion generator hardware from a previous AEDC investigation [2] was used where possible.

²All figures appear in Appendix A.

A detailed description of the ADG system is presented in [2]. A general description with details of major features is presented in this study.

The high-pressure air module supplied secondary air to the airjet supply manifold at the desired pressure level at the temperature matching the primary inlet air temperature. A bypass system allows the secondary air system to be temperature-conditioned prior to introducing the flow into the primary engine inlet stream.

The airjet assembly (Figure 3) consists of the supply manifold, 56 flow control valves, 24 aerodynamically designed airjet struts mounted in the spool assembly which contains the 56 air injection ports, and associated piping. The control valves, upon either opening or closing, can be manually- or computer-operated.

For this investigation, the 56 air control valves were individually controlled by a digital computer. Engine inlet pressure level was determined from 40 total-pressure measurements at the engine face, with each measurement representing an equal portion of the inlet area. Although the inlet duct diameter was constant from the ADG assembly to the engine face, the center bullet nose at the engine face reduced the inlet flow area. Thus, the 40 total-pressure measurements made at the engine face were transposed to 40 valves, each representing an equal portion of the flow area at the jet assembly location. The 40 transposed local pressure ratios were then interpolated to the

locations of the 56 jets. Circumferential interpolation was linear, whereas radial interpolation was from a second-order Lagrangian curve fit. The computer compared the actual pressure level at each spatial location to the desired level and commanded the airjet valves to either open or close to establish the desired pressure levels.

The command to each individual airjet valve was determined by the digital computer program logic. Basic logic functions determined the overall pattern root-mean-square error (RMSE) and the individual error at each spatial location, as defined in Chapter III, Section III.2. The selection of control valves to be repositioned was determined by comparing the error in local pressure level with the overall pattern error. Those valves controlling secondary airflow to areas with local pressure errors greater than the overall pattern error were directed to move, and all remaining valves were unchanged.

II.1.2 Test Equipment

The engine used for this test program was an F101-GE-100 engine which has been extensively tested at the AEDC. Information obtained during these investigations pertaining to the engine component stability and screen-generated inlet distortion patterns served as a baseline for this investigation. The engine is an augmented, mixed flow, turbofan engine with aerodynamically coupled low- and high-pressure sections and a variable area

exhaust nozzle. The low-pressure section consists of a two-stage fan driven by a two-stage, low-pressure turbine. Variable inlet guide vane flaps are used on the fan. The high-pressure section is composed of a nine-stage compressor, an annular combustor, and a single-stage, air-cooled, high-pressure turbine. The compressor utilizes variable geometry inlet guide vanes and stator vanes for the first three stages. The standard convergent-divergent nozzle was not installed for this test. Instead, a convergent nozzle with extended flaps was used to allow reduction of the normal minimum area. This provided a mechanism for artificially inducing fan stalls by nozzle closure.

Three distortion screens were used during the test program as a baseline for direct comparison with the ADG system performance. The three screens used (Figure 4) simulated classical hub radial and 180-deg, 1/rev patterns and an F101 specification pattern. The desired total-pressure patterns were defined from measured inlet pressure values with the screens installed and were duplicated by the ADG system.

II.1.3 Test Cell and Installation

Propulsion Development Test Cell (J-2) [5] is a water-cooled test cell which has a 20-ft-diameter by 69-ft-long test section. The engine was rigidly attached to the floating portion of the overhead water-cooled thrust

stand. The engine was isolated from the engine inlet ducting, which is also mounted from the thrust stand, by a flexible seal. The floating thrust stand was isolated from the test cell ducting by a labyrinth seal.

The initial testing was with distortion screens, and the airjet strut assembly was not installed. The screen location is just downstream of the airjet strut location (Figure 3a) and the screen support grid remained installed during all testing.

II.1.4 Instrumentation

Instrumentation was provided to measure steady-state aerodynamic pressures and temperatures; dynamic pressures; primary and secondary airflows; fuel system pressures, temperatures, and flowrates; rotational speeds; exhaust nozzle area; engine accelerations; and engine control system signals. Gas path pressure and temperature measurements were made at the engine stations shown in Figure 5. A discussion of the general instrumentation systems, calibration techniques, and data conditioning and recording systems may be found in [6].

Steady-state, transient, and dynamic total pressure were each measured at 40 locations in the engine front frame. All three measurement systems shared a common port at each location. These total-pressure ports were arranged in five equal area rings, with eight ports per ring.

For this investigation, bonded strain-gage-type pressure transducers were used for the ADG system feedback signals and for all transient data acquisition. These systems had a 10-Hz minimum response and were calibrated by substitution of a resistance equivalent to a known pressure across the transducer. For high-frequency pressure measurements Kulite^(R) close-coupled transducers were mounted within the engine probes. This system had a minimum response of 1,000 Hz. The Kulite transducers were pretest calibrated by applying a known pressure across all transducers in both the increasing and decreasing pressure mode. This was accomplished by a pneumatic system plumbed to each transducer that allowed a known pressure to be applied to either or both sides of the sensor to obtain a zero pressure level signal. Because of the tendency of the transducers to shift with temperature and time, each transducer was electrically nulled and a single-step calibration applied within 30 minutes prior to obtaining dynamic data. This dynamic data was processed through an RMS to DC converter for on-line display.

Temperature measurements of the primary airflow were made by thermocouples placed in rakes upstream of the ADG assembly. Because the secondary airflow was temperature-conditioned to match the primary airflow at the inlet, it was not necessary to make temperature measurements at the engine face [2]. All data outputs were

recorded on FM multiplex tape systems for off-line analysis. Posttest estimates of measurement uncertainties for the critical parameters are presented in [6].

II.2 Test Procedure

II.2.1 Test Conditions

Conditioned air was supplied to the engine inlet at the total pressure and temperature required to simulate the desired test condition. Although testing was not conducted at the simulated altitudes normally associated with the specific pattern being imposed, this effect is considered to have negligible influence, as will be discussed later. In fact, inlet pressures were reduced to minimize engine deterioration during the induced engine surges, and the inlet temperature was reduced to allow adequate turbine temperature margin to obtain fan stalls without causing fan speed reduction. A summary of the test matrix is presented in Table 1, Appendix B.³

II.2.2 Engine Operation

Engine stability was evaluated without inlet distortion ("clean inlet"), with inlet distortion screens, and with distortion patterns produced by the ADG system. The engine was started and stabilized for 15 minutes at a specific corrected airflow for each pattern.

³All tables appear in Appendix B.

The engine was intentionally stalled to determine the surge pressure ratio of both the fan and the high-pressure compressor and to compare the results with distorted and undistorted inlet conditions. Whenever engine stalls occurred, the power lever was immediately reduced to the idle position to preclude engine damage. If the stall persisted, the engine was shut down. Fan stalls were induced along constant speed lines by exhaust nozzle closure. Incremental nozzle closure was accomplished by remote control. Compressor stalls were induced by step increases in fuel flow to the combustor.

CHAPTER III

METHOD OF ANALYSIS

Comparison and evaluation of the airjet distortion generator system and distortion screens requires that the flow field at the engine inlet be characterized for both distortion systems. The most general flow field is both time and space dependent [7]. Figure 6 shows the variation of total pressure with time for both ADG system distortion and screen distortion for a typical pattern. The time variant portion of the total pressure results in a continuously changing isobar contour map (Figure 7). Although the total-pressure time traces and the sequence of contour maps define the flow field quite well, it is difficult to analyze data and make comparison of distortion techniques in this form. For this reason certain calculated parameters have been generally adopted, providing a description of the distortion and a quantitative analysis of both the engine inlet flow field and the engine component surge characteristics.

Evaluation of data obtained during this investigation to determine the suitability of the ADG system for replacing varying porosity screens required a three-fold approach. First, data obtained from inlet total-pressure distortion screens and the ADG system were compared on a

steady-state basis. Second, data obtained by the two methods were compared for their dynamic content. Finally, an evaluation was made of the effects on engine surge characteristics of distortion patterns generated by the two methods.

The indices which are described in the following paragraphs were used to characterize the inlet flow field.

III.1 Distortion Analysis

III.1.1 Absolute Distortion

The distortion level achieved on a pattern generated by either distortion screens or the ADG system can be described by the variation of total pressure over the engine inlet plane. The parameter commonly used to describe absolute distortion, DIST1, represents the range of the total-pressure variation normalized by the average total-pressure [2]. In equation form:

$$\text{DIST1} = \frac{P_{1\text{max}} - P_{1\text{min}}}{P_{1\text{avg}}} \times 100, \text{ percent} .$$

This parameter is a widely-used means of specifying the overall extremes of the pressure maldistribution, but this index lacks the ability to characterize the distortion spatial extent and location.

III.1.2 Circumferential and Radial Distortion (Steady-State)

Circumferential distortion, the total-pressure variation occurring at a constant radius about an inlet centerline, and radial distortion, the total-pressure variation at a constant angular location of the inlet, are not considered to occur simultaneously in "classical patterns." An ideal "tip radial" pattern has only radial distortion with a low total-pressure region in the tip (Figure 8a). Similarly, a "hub radial" pattern has only radial distortion with a low total-pressure region in the hub (Figure 8a). A "180-deg" pattern has only circumferential distortion with one-half or 180 degrees of the pattern having lowered total-pressure. Because an engine component will cycle through a high-, then low-pressure region once for each revolution, this pattern is referred to as a "180-deg, 1/rev pattern" (Figure 8a). While there are only three types of classical patterns, each type can occur at various engine speeds and with differing levels of distortion. For this investigation variations of the three types will be referred to as distinct classical patterns; that is, tip radial pattern at 100 percent fan speed, and tip radial pattern at 90 percent fan speed. "Composite patterns" are composites of these classical patterns combining circumferential and radial distortion to produce an overall pattern.

Patterns having the same overall distortion levels (DIST1) may have different effects on engine component response if the low total-pressure regions are of different spatial extent over the engine inlet, or if the location of the low total-pressure region in one pattern does not correspond to the low total-pressure region in the second pattern. Thus, in addition to the overall distortion parameter, another quantitative description of the total-pressure gradient is needed. A valuable means of description is provided by the General Electric distortion indices, IDC and IDR, which describe circumferential and radial distortion, respectively [8]. In this investigation, the extent and magnitude of spatial distortion was determined by total-pressure probes arranged in five rings with eight probes per ring (Figure 8b). Hence, circumferential distortion can be described by five values, one for each ring, representing the total-pressure variation about a given ring. The circumferential distortion index is defined as:

$$IDC = \frac{P_{1\text{ ring avg}} - P_{1\text{ ring min}}}{P_{1\text{ ring avg}}} .$$

In addition to five values to describe the circumferential distortion at each ring it is usual to have a single number description of the pattern total-pressure circumferential distortion. Maximum circumferential distortion (IDCM) is

defined as the larger of the average IDC of the two inner rings (1 and 2), or the average IDC of the two outer rings (4 and 5). If the inner two rings (hub) have a higher average IDC, the maximum IDC is given as IDC_M(H). Similarly, a higher average IDC in the outer two rings (tip) is denoted as IDC_M(T).

Radial distortion can also be described by five values, one for each ring, representing the total-pressure variation from ring to ring. The radial distortion index is defined as:

$$IDR = \frac{P_{1\text{face avg}} - P_{1\text{ring avg}}}{P_{1\text{face avg}}} .$$

The maximum radial distortion (IDRM) is defined as the larger IDR value of the innermost ring (1) or the outermost ring (5). Designation of the location of the maximum radial distortion (hub ~ IDRM(H) or tip ~ IDRM(T)) is consistent with the nomenclature of the circumferential distortion (IDCM(H) or IDCM(T)).

III.1.3 Circumferential and Radial Distortion (Dynamic)

In addition to steady-state circumferential and radial distortion an evaluation was made of the dynamic distortion. In radial patterns, radial distortion is dominant, so dynamic values of the circumferential and radial distortion indices (IDCD, IDRD) are given at the instant of largest radial distortion. Maximum values are

presented as IDCMD and IDRMD. For 180-deg, 1/rev patterns and most composite patterns circumferential distortion is dominant, so dynamic values of the circumferential and radial distortion indices are given at the instant of largest circumferential distortion. Again, maximum values are presented as IDCMD and IDRMD.

III. Pattern Match Capability

The ability of the ADG system to match a pattern created by an inlet distortion screen was evaluated on a probe-to-probe basis. A pattern match requires the ADG system to not only achieve the same overall distortion level, but also to produce the same total pressure at each probe location as that produced by the distortion screen. A quantitative description of inlet pattern error, or mismatch, is given by the parameter RMSE defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N \left[\left(\frac{Pl_{\text{measured}}}{Pl_{\text{desired}}} \right)_i - 1 \right]^2}{N}} \times 100, \text{ percent},$$

where Pl_i is total-pressure measured at probe i , and N is the number of total-pressure probes.

III.3 Turbulence Analysis

III.3.1 Evaluation of Turbulence Amplitude

As an indication of the amplitude of the inlet total-pressure turbulence, root-mean-square (RMS) values for each total pressure were determined using an electronic analog wave analyzer. Mathematically, RMS is defined for a function $p(t)$ as:

$$RMS_i = \sqrt{\frac{1}{T} \int_0^T (p(t)_i)^2 dt} ,$$

where T is the time span of the data, and $p(t)_i$ is the value of the time variant total pressure at probe i . The RMS values used in this study are normalized by the face-averaged total pressure (PF) and are presented in RMS distribution maps.

The face-averaged value of RMS/PF is defined as

$$\frac{PRMS}{PF} = \frac{1}{N} \sum_{i=1}^N \frac{RMS_i}{PF} = \frac{1}{(PF)NT^{1/2}} \sum_{i=1}^N \sqrt{\int_0^T (p(t)_i)^2 dt} .$$

III.3.2 Evaluation of Turbulence Frequency

In addition to the RMS amplitude, it is important to know the rate at which flow fluctuations occur. Only fluctuations of a frequency lower than approximately the fan rotational frequency will be recognized as spatial distortion by the fan [9]. The power spectral density

function (PSD) is helpful in determining the frequency distribution of the amplitude of the fluctuations. The PSD function was computed using an electronic analog wave analyzer and presented graphically as a function of frequency. The PSD function of a stationary signal is mathematically defined as:

$$\text{PSD} = \lim_{T \rightarrow \infty} \lim_{\Delta f \rightarrow 0} \frac{1}{(\Delta f)T} \int_0^T (Y(t, f, \Delta f))^2 dt ,$$

where T is the time span of the data, f is the bandwidth of the electrical filter used, and $Y(t, f, \Delta f)$ is the instantaneous value of the data waveform at time t , within the bandwidth Δf . For this investigation, all engine face data were filtered at 125 Hz, which is the fan's rotational frequency. The PSD function indicates the energy distribution with frequency and reveals the existence of any discrete frequency components of the total input signal. The PSD functions presented in this study were normalized by the steady-state total pressure as:

$$\frac{\text{PSD}}{(P_1)^2} = \frac{(\Delta P_1^2 / \text{Hz})}{(P_1)^2} = \frac{(\Delta P_1 / P_1)^2}{\text{Hz}} .$$

III.4 Component Stability Analysis

III.4.1 Surge Pressure Ratio Comparison

In order for the ADG system to be considered an acceptable alternative to distortion screens, it is necessary to identify any differences in engine stability produced by the two distortion methods. The engine components of interest, the fan and high-pressure compressor, were intentionally stalled, as described in Chapter II, Section II.4. For this test, distortion was produced both by the ADG system and screens at the same conditions previously used for screen distortion investigations. Differences in engine response were found by comparing the component pressure ratio at which surge occurs with ADG-produced distortion to the component pressure ratio at which surge occurs with screen-generated distortion (Figure 9). The following index was defined for this comparison:

$$\text{surge pressure ratio comparison} = \frac{\text{PRS}_{\text{ADG}} - \text{PRS}_{\text{desired}}}{\text{PRS}_{\text{desired}}} \times 100, \text{ percent} ,$$

where PRS is the component pressure ratio at surge, with $\text{PRS}_{\text{desired}}$ defined as the pressure ratio at which surge occurs with screen distortion.

III.4.2 Airflow Calculations

Using the component map (Figure 9) to compare surge pressure ratios required accurate engine airflow

measurements. The airflow passing through the engine was the sum of the primary airflow (flow upstream of the ADG assembly) and the airflow injected into the inlet airstream by the ADG system. Total airflow was calculated as:

$$WY1 = WY1P + WSA ,$$

where WY1P is the primary airflow, and WSA is the secondary airflow injected into the airstream by the ADG system.

The primary airflow was measured by using the test cell critical flow venturis. The secondary airflow to the ADG system was measured by using a standard ASME sharp-edged orifice. The engine corrected airflow was calculated using the expression:

$$W1R = WY1 \left(\frac{PSLS}{P1} \right) \sqrt{\frac{T1}{TSLs}} ,$$

where P1 is the average engine face total pressure, T1 is the average engine face total temperature, and PSLS and TSLs are the sea-level standard pressure and temperature, respectively.

III.5 Calculated Parameter Uncertainties

Uncertainties in the calculated parameters result from the accumulation of the uncertainties in the measured parameters. Uncertainties of the calculated parameters are determined as shown in [10] and are presented in Tables 2 and 3.

CHAPTER IV

RESULTS AND DISCUSSION

A performance evaluation of an airjet distortion generator system was conducted to determine if an airjet distortion generator system could replace varying porosity screen overlays for inlet pressure distortion testing of turbojet and turbofan engines.

The scope of this investigation not only included the assessment of the fidelity with which the ADG could produce a desired parametric total-pressure pattern, but also provided (1) a direct comparison of F101-GE-100 turbofan engine surge characteristics with distortion patterns generated by both screens and the ADG; (2) engine surge characteristics with selected composite patterns simulated with the ADG and compared to historical screen data; and (3) a documentation of the effect of Reynolds number on the surge characteristics with inlet distortion patterns set by the ADG.

First, the test results relative to the primary objective are presented, and second, additional test results are presented concerning the operation and performance of the airjet distortion generator system.

IV.1 Inlet Total-Pressure Pattern Fidelity

The ADG system is designed to produce steady-state, total-pressure spatial distortion of the airflow at the inlet of a turbine engine. The fidelity of the inlet distortion patterns produced by the ADG system was evaluated for 10 classical and 12 composite inlet distortion patterns. Of these, six classical and two composite distortion patterns were also produced during these tests using screen overlays installed in the engine inlet ducting. Because these eight patterns were produced during the same test program as the ADG patterns, and because the instrumentation was more complete during these tests, they were considered to give a better direct comparison to the ADG patterns. Consequently, these six classical and two composite patterns are referred to as "baseline patterns." Distortion pattern measurements were available from previous engine and inlet testing, through the engine manufacturer, for the remaining four classical and ten composite screen-generated distortion patterns. Measurements were also available from the same sources for three of the classical patterns included in the baseline patterns. The ADG system was then used to reproduce all of the screen-generated inlet pressure patterns.

IV.1.1 Comparison of ADG Patterns to Screen-Generated Baseline Patterns

Screen-generated inlet distortion patterns were produced for six classical patterns (180-deg, 1/rev and 50 percent hub radial patterns at fan speeds of 90, 95, and 100 percent) and two composite patterns (two F101 specification patterns) during baseline testing. Each screen-generated pattern was then attempted using the ADG system. Steady-state, total-pressure distortion pattern quality can be described by the pattern characteristic appearance and distortion level DIST1.

Pattern characteristics, as described by an isobar map and the value of DIST1 at the engine inlet, are presented for a clean inlet in Figure 10a. The map indicates that there is essentially no inlet distortion when secondary air is not injected. Isobar maps of the baseline patterns are presented in Figures 11 through 18. For each pattern, the ADG system produced similar areas of high and low total pressure and maintained similar area contours to those produced by the distortion screens. The overall distortion level (DIST1) of the classical patterns produced by the ADG system agreed with the screen-produced distortion level within 1.6 percent DIST1. Figure 14 is a typical result, while Figure 10 illustrates the poorest agreement. For the composite patterns agreement was within 6 percent DIST1.

An evaluation of the circumferential and radial distortion can be made with the use of the parameters IDC and IDR. IDC and IDR values for a clean inlet are shown in Figure 10c. For the three classical, 50 percent hub radial patterns (Figures 14 through 16), IDR values for patterns produced by the ADG system were slightly lower in magnitude in both the hub and tip regions than the IDR values for the screen-produced patterns (maximum $\Delta IDR = 0.01$). For the three 180-deg, 1/rev patterns (Figures 11 through 13), IDR values were slightly higher in magnitude in both the hub and tip regions for ADG system-produced patterns than the IDR values for screen-produced patterns (maximum $\Delta IDR = 0.02$). In the composite patterns (Figures 17 and 18) the ADG system again gave lower IDR values in the hub region, but IDR values in the tip region were slightly higher than those from the screen-produced patterns (maximum $\Delta IDR = 0.02$). For the three 50 percent hub radial patterns (Figures 14 through 16), IDC values in the hub region for both ADG system- and screen-produced patterns agreed, but in the tip region the ADG system patterns were somewhat higher (maximum $\Delta IDC = 0.04$). For the 180-deg, 1/rev, low-speed fan surge pattern (Figure 11), IDC values agreed in the tip region, but were low ($\Delta IDC = 0.02$) in the hub region for the ADG system pattern. Both the 180-deg, 1/rev, high-speed fan surge and core surge patterns (Figures 12 and 13) resulted in slightly lower IDC values in the hub and tip region (maximum $\Delta IDC = 0.02$). In both

composite patterns (Figures 17 and 18) the ADG system gave slightly lower IDC values in the hub region and slightly higher values in the tip region (maximum $\Delta IDC = 0.02$). IDR and IDC values as functions of ring number are also given in Figures 10 through 18.

Although pattern characteristics and distortion level are good indications of pattern quality, the specific definition of each inlet pattern should be made on the basis of a comparison of individual pressure levels at the specific spatial locations. Individual pressure values for each pattern are also compared in Figures 11 through 18. The overall agreement between the measured and desired local pressure levels can be quantified by the RMSE index. For the eight patterns, the RMSE ranged from 1.1 to 2.5 percent. This is less error than that nominally obtained with the screens using current design techniques [2]. The largest RMSE generally occurred at the highest distortion levels, as typified by Figure 13. Individual RMSE values are given in Table 4. In general, the steady-state agreement between the ADG system patterns and screen patterns was good, with excellent agreement on the six classical patterns.

A survey of time variant total pressure was made for three of the five classical and the two composite base-line patterns produced by both the ADG system and by inlet distortion screens. To get a quantitative comparison of the turbulence levels produced by the ADG system and an

inlet distortion screen, RMS values were calculated for each spatial location. Characteristics of the time variant total pressure can be displayed in total-pressure RMS distribution maps. Figures 19 through 23 present maps of normalized total-pressure RMS and PRMS/PF (face-averaged normalized RMS) for the three classical and two composite patterns produced by both distortion methods. A map of normalized total-pressure RMS for a clean engine inlet is also included in Figure 10b. In general, inlet total-pressure distortion patterns produced by distortion screens showed approximately one-half the values of PRMS/PF (0.4 to 0.6 percent) as the same distortion patterns produced by the ADG system (1.1 to 1.3 percent). In the screen-produced patterns the highest levels of total-pressure RMS were consistently observed to be near the outer wall region, similar to the RMS distribution for the clean inlet. However, from the screen-produced patterns the "highest" levels of PRMS are still quite low (0.7 to 0.8 percent). For distortion patterns produced by the ADG system, the highest levels of total-pressure RMS fall in the regions of steepest total-pressure gradient, remaining lower in the areas of relatively constant high and low total pressure, as illustrated by Figures 15 and 20, and by Figures 17 and 22.

The similarity in the turbulence distribution of clean inlet pattern and the screen-generated patterns indicates that the turbulence present in the screen patterns

results primarily from the duct boundary layer, and that most of the turbulence generated by individual wires in the screen dampens out before reaching the engine face [11]. The turbulence distribution for the ADG system patterns indicates that the turbulence is created primarily in the mixing zones between regions with high momentum (high total-pressure) and regions with low momentum (low total-pressure). This turbulence persists downstream to the engine face.

For a full-scale inlet operating at representative flight conditions, low total-pressure regions appear both as a result of shock losses and because of the wall boundary layer. These conditions also produce turbulence, resulting in the highest turbulence occurring in the low-pressure regions. Because of their origin, the low-pressure region, and consequently, the highest turbulence, occur near the inlet wall, and their magnitudes are strongly dependent on the flight Mach number. Recent testing of the North American B-1 inlet [12] revealed that the PRMS/PF levels for the real inlet vary from 0.6 percent for subsonic flight conditions, to 1.4 percent for supersonic flight conditions. The lower value is comparable to the screen-generated turbulence, while the latter is comparable to the ADG system-generated turbulence. Although each distortion method seems to be better suited to a specific flight regime in terms of turbulence levels,

it is evident the screen system can better generate turbulence in the same location as the real inlet.

An evaluation of the dynamic, circumferential and radial distortion can also be made using the parameters IDC and IDR. For the 50 percent hub radial patterns, instantaneous values of IDC and IDR are typically presented at the time of maximum IDR. For the composite patterns, instantaneous values for IDC and IDR are typically presented at the time of maximum IDC. Dynamic values for IDC and IDR as functions of ring number are presented in Figures 19 through 23, along with the steady-state IDC and IDR for the same patterns. Dynamics had little effect on the radial gradient (maximum $\Delta IDR = 0.01$), but had slightly larger effect on the circumferential gradient (maximum $\Delta IDC = 0.05$). The variation of circumferential distortion is more significant since the engine is more sensitive to circumferential distortion than radial distortion.

To evaluate the frequency and energy of the time variant total pressure, a comparison of the power spectral density functions for each pattern is also presented in Figures 19 through 23. In general, the functions for the ADG system patterns are slightly higher and flatter than the PSD functions for the screen patterns. The higher levels indicate more turbulent energy in the ADG system pattern; whereas, the flatness indicates a distribution

closer to that of white noise, as would be expected from the jet mixing, as indicated in Figure 19.

A summary of the results obtained during the baseline testing is presented in Table 4. These results allowed an evaluation of the operation of the ADG system, but more information was needed to examine the limitations of the system.

IV.1.2 Comparison of ADG Patterns to Other Screen-Generated Patterns

Steady-state inlet total-pressure pattern measurements were available for an additional seven classical and ten composite patterns generated by distortion screens. Each pattern was reproduced by the ADG system, and the limits of its operation were evaluated.

Pattern characteristics and distortion levels are shown in Figure 24a through q in the form of isobar maps and corresponding DIST1 values for each pattern. Similar areas of high- and low-pressure were produced by the ADG system, as were shown in the screen-produced patterns. In all but the most highly distorted patterns, similar pressure contours were maintained.

Duplications of four 180-deg, 1/rev, square wave patterns with distortion levels varying from 16.3 to 32.2 percent total distortion and varying pressure gradient severity were attempted with the ADG system. RMSE values ranged from 1.5 to 6.3 percent, with smaller values for

patterns with less severe gradients. Results for these lower values of IDC are typified by Figure 24b. Distortion level disagreement ranged from 0.0 to 10.2 percent DIST1, with best agreement for patterns with lower total distortion levels. Figure 24a is typical for DIST1 agreement, while Figure 24d is typical of patterns with large differences in distortion.

Three classical tip radial patterns were attempted with total distortion levels ranging from 16.2 to 23.2 percent and varying gradient severity. RMSE values ranged from 1.8 to 4.3 percent as gradient severity increased from a pattern maximum IDR value of 0.081 to 0.105 (Figure 24e through g). Distortion level agreement ranged from 1.4 percent (Figure 24g) to 8.9 percent (Figure 24e), with the worst case occurring at the highest total distortion level.

Ten composite inlet total-pressure distortion patterns were attempted with total distortion levels ranging from 13.5 to 24.7 percent, and varying combinations of radial and circumferential distortion. These results are displayed in Figure 24h through q. RMSE values ranged from 2.2 to 5.1 percent, while distortion level agreement ranged from 0.3 to 7.9 percent, again with the worst agreement occurring at the highest total distortion level (Figure 24o).

From these tests it was concluded that the ADG system could closely match patterns at high corrected air-flow rates (high fan speeds), but could not match patterns

with severe pressure gradients at lower corrected airflows (low fan speeds). This indicates that with lowered velocity in the primary flow the counterflowing jets were not as effective in creating distinct gradients in the flow field. For a tip radial pattern with 100 percent fan speed, a radial gradient of 16.2 percent was achieved, where only 10.9 percent radial gradient was achieved at 75 percent fan speed (Figure 24f and g). This indicates that the current ADG configuration is too limited in both radial and circumferential distortion-generating capability to match the most severe patterns.

A summary of the results obtained during the comparison with other screen-generated patterns is shown in Table 5.

IV.2 Engine Stability

For the purpose of this discussion, engine stability shall be considered as the surge-free operation of the engine compression system. The current method of producing steady-state, total-pressure distortion for turbine engine stability testing uses the technique of installing various porosity screens in the engine inlet. In order for the ADG system to be an acceptable alternate method, it is necessary to identify any differences in engine stability with distortion produced by the two methods. During this investigation, engine stability was

determined for several classical and composite distortion patterns produced by the ADG system. In addition, engine stability was determined for three of the classical and two of the composite distortion patterns produced by inlet screens. This procedure provided a direct comparison of engine operation with the same pattern produced by the two methods. Engine stability for the remaining screen-generated patterns was available from previous engine tests.

IV.2.1 Comparison of Engine Stability with ADG Patterns and Screen-Generated Baseline Pattern

Engine stability was determined for three classical patterns (50 percent hub radial patterns at 90 to 100 percent fan speeds) and two composite patterns (F101 specification patterns), with each pattern being produced by both inlet distortion screens and the ADG system. The agreement between the patterns produced by the two methods was discussed in Section IV.1.1. This approach provided a direct comparison for engine operation under each method of inlet total-pressure distortion.

Fan surges were produced with the 50 percent hub radial pattern and the engine operating at 90 and 100 percent fan speed and loaded by incremental nozzle closure. The fan operating level with ADG system distortion was 1.4 percent higher than the operating level with screen-produced inlet distortion at the 90 percent speed condition.

At the higher fan speed, the fan operating level with ADG system distortion was 2.6 percent higher than the operating level with screen distortion. The ADG system produced higher surge pressure ratios than were produced by screen distortion, with values of 1.0 and 2.3 percent at low-speed fan surge and high-speed fan surge, respectively.

A surge on the core compressor also occurred with the 50 percent hub radial pattern and the engine loaded by step increases in fuel flow to the combustor. The core surge pressure ratio was 1.4 percent lower with ADG system distortion than the surge pressure ratio with screen distortion.

The engine fan and core were both surged with the composite F101 specification pattern. The fan operating level was 3.5 percent higher with ADG system distortion than with screen distortion. Surge pressure ratios for both engine components were less than 1 percent higher (0.4 percent for the fan and 0.6 percent for the core) with ADG system distortion than with screen distortion.

To evaluate any changes in surge margin, both the operating level and the surge pressure-ratio must be considered. A comparison of the surge margins with ADG distortion and screen distortion is presented in Figure 25. In general, the surge margin was slightly lower with ADG system distortion than with screen distortion.

For these baseline tests, engine stability agreement was good. Surge pressure ratio with screen- and ADG system-produced distortion agreed within 2.6 percent. Results are summarized in Table 6.

IV.2.2 Comparison of Engine Stability with ADG Patterns and Other Screen-Generated Patterns

Engine stability was determined for three 180-deg, 1/rev distortion patterns, one modified 180-deg, 1/rev distortion pattern, two 50 percent tip radial patterns, and one F101 specification pattern. These patterns represent a broad range of distortion, including some steep pressure gradients. Comparisons were made with engine stability from previous tests. The agreement between these patterns produced by the two distortion methods was discussed in Section IV.1.2.

High- and low-speed fan surges were induced with the ADG system producing the 180-deg, 1/rev distortion pattern. Surge pressure ratio for the high-speed surge was 1.6 percent lower with ADG-produced distortion, while the low-speed surge pressure ratio was 2.6 percent higher than the corresponding screen value. A core surge also was produced, giving a 0.9 percent lower surge pressure ratio under ADG system distortion. Using the modified 180-deg, 1/rev distortion pattern a fan surge was obtained with the ADG system producing a 6.3 percent higher surge pressure ratio than resulted with screen distortion.

High- and low-speed fan surges were again produced with ADG system-produced, 50 percent tip radial distortion. Surge pressure ratio for the high-speed surge was 2.3 percent lower with ADG system distortion, while the low-speed surge pressure ratio was 15.9 percent higher than the corresponding screen value. Finally, a fan surge was obtained with the F101 specification pattern. The surge pressure ratio with ADG system distortion was 13.8 percent higher than the corresponding screen values.

These results indicate that, when the patterns are matched with a 3 percent RMSE, there is little difference in the engine's stability (-2.3 to +2.6 percent in surge pressure ratio). However, for the patterns not well-matched (RMSE = 4.3 to 6.3 percent), large disagreements in the engine's stability occurred, which, as described below, appear to be solely the result of the mismatched steady-state distortion pattern. A summary of the results obtained during this investigation is presented in Table 7.

IV.2.3 Evaluation of Engine Stability Differences

As described above, in some cases, surge pressure ratio with ADG system-generated inlet distortion was significantly different from surge pressure ratios with screen distortion. However, the patterns with worse surge pressure ratio agreements also had high RMSE values, indicating that the engine was not actually being subjected to identical patterns. Distortion sensitivity curves

(Figure 26) have been generated by General Electric for the F101, giving surge pressure ratio loss as a function of average IDC for 180-deg, 1/rev patterns, and maximum IDR for tip radial and hub radial patterns. These curves are based on a large number of engines tested in various facilities, using screen distortion. By using these curves to correct for mismatches in the screen and ADG distortion parameters, a better evaluation can be made of any effects the ADG system itself had on surge pressure ratio. Seven patterns were corrected for both steady-state and dynamic values of IDC and IDR; results are summarized in Table 8. In general, surge pressure ratio disagreement between screen- and ADG-produced distortion was reduced to less than 4 percent. This remaining disagreement is partially because of engine-to-engine and facility-to-facility tolerances. In addition, the use of the distortion sensitivity curves required that each pattern be treated as if it contained only circumferential or radial distortion, and not both. Although these seven patterns were each predominantly either circumferential, or radial, in distortion, they all did contain both directions of distortion to some degree. This slight additional distortion can cause changes in surge pressure ratio that are not accounted for. When considering these factors, the 4 percent disagreement implies that there are no discernible differences in the engine stability response between a screen-produced and an ADG-produced flow field.

IV.2.4 Effect of Reynolds Number on Patterns

To determine the effect of changes in Reynolds number on inlet total-pressure pattern fidelity, two composite patterns (F101 specification pattern at high-speed fan surge and F101 specification pattern at core surge) were matched by the ADG system at inlet pressures of 8, 4, and 2 psia. This corresponds to Reynolds number indices (RNI) of 0.6, 0.3, and 0.15, where Reynolds number index is defined as the ratio of the represented Reynolds number to the Reynolds number at sea-level-static conditions. For both patterns, results were consistent at each Reynolds index; as Reynolds number index decreased, both RMSE and DIST1 increased slightly. However, values for RMSE varied by no more than 0.2 percent for the fan surge, and 0.4 percent for the core surge. This is within the repeatability of the ADG system (Section IV.3.2). DIST1 values varied by no more than 1.6 and 2.3 percent for the fan and core surge patterns, respectively. Individual values for RMSE and DIST1 are presented, along with isobar maps at each Reynolds number in Figures 28a and 29a. Radial distortion, as shown by IDR, remained essentially unchanged under each condition for both patterns. However, values for IDC indicate the circumferential distortion in the tip region increased slightly for both patterns as Reynolds number was decreased. IDC and IDR values for these two patterns are presented as functions of ring number in Figures 28b and 29b.

For both the fan surge and core surge patterns, the magnitude of the time variant inlet total pressure increased with decreasing Reynolds number. PRMS/PF increased from 1.2 to 1.4 to 2.1, corresponding to Reynolds number indices of 0.6, 0.3, and 0.15 for the core surge pattern (Figure 30a), while PRMS/PF values for the fan surge were 1.4, 1.4, and 2.4, respectively (Figure 31a). PSD functions for both patterns also showed a slight increase with decreasing Reynolds number (Figures 30b and 31b). However, these variations in PRMS/PF and PSD are within the repeatability of the data system at the pressure level required to achieve a Reynolds number index of 0.15. Thus, it was concluded that, any variations in results because of differing Reynolds numbers were smaller than test-to-test variations.

IV.3 System Performance Reliability

IV.3.1 Stability of ADG System Patterns

The high degree of flexibility associated with the ADG system was demonstrated for two classical patterns (180-deg, 1/rev, square wave pattern and 50 percent hub radial pattern). The capability of the ADG system to produce a constant distortion pattern over a range of corrected engine airflows from 308 to 286 lbm/sec for the 50 percent hub radial pattern, and a range of 298 to 271 for the 180-deg, 1/rev, square wave pattern is demonstrated

by the isobar maps of the patterns presented in Figures 32 and 33. At each airflow level, the pattern characteristics were reproduced with the distortion level (DIST1) maintained in both cases to within 1 percent absolute distortion (Figures 32a and 33a). Both patterns showed almost no change in radial or circumferential distortion, as shown by their respective IDC and IDR values (Figures 32b and 33b). This allows patterns to be set with the engine on its normal operating line, and held while the engine is surged.

IV.3.2 Repeatability of the ADG System Patterns

For the ADG system to be a viable replacement for inlet distortion screens in engine testing, it must not only reproduce inlet total-pressure variations as accurately as screens, it must also demonstrate a high degree of operational reliability.

To further demonstrate the repeatability of the ADG system patterns, a single, classical pattern (180-deg, 1/rev square wave) was simulated by the ADG system at three different times throughout the investigation. Isobar maps again demonstrate the capability of the ADG system to produce a constant inlet distortion pattern, (Figure 34). Distortion levels varied by only 0.5 percent, while RMSE was maintained to within a 0.4 percent spread. Maximum values of IDC and IDR also showed little change.

Twice during this investigation a comparison of the time variant inlet total-pressure was made for a 50 percent hub radial pattern. Both patterns produced similar RMS distribution maps with PRMS/PF disagreeing by only 0.1 percent (Figure 35a). PSD functions for both patterns were essentially identical (Figure 35b).

The operational reliability of the ADG system was excellent, with no major operational problems experienced throughout the investigation. One limiting factor in the ADG system operation is the quantity of high-pressure air used. However, minimizing the time required to set a distortion pattern allows more time for inlet distortion engine operation. During this investigation, pattern set times were consistently under two minutes, averaging approximately one and one-half minutes.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A performance evaluation of an airjet distortion generator system was conducted with 10 classical and 12 composite total-pressure distortion patterns. Engine stability response was determined and compared for inlet total-pressure distortion produced by inlet screens and the ADG system. Significant results of this evaluation are summarized as follows:

1. The root-mean-square error of the steady-state, inlet total-pressure pattern match produced by the ADG system varied from 1.1 to 2.5 percent for the baseline patterns. This is less error than normally obtained for screens using current design techniques.
2. The root-mean-square error of the steady-state, inlet total-pressure pattern match produced by the ADG system varied from 1.5 to 6.3 percent for patterns duplicating screen-generated patterns from other engine/rig tests, indicating that the current ADG configuration is too limited in both radial and circumferential distortion-generating capability to match the most severe patterns.

3. Local inlet turbulence levels (PRMS/PF) measured with screen distortion levels were less than 1 percent. Local turbulence levels measured with ADG system distortion were less than 2 percent. Based on limited inlet data, it appears each method seems to be better suited to a specific flight regime in terms of turbulence level. However, the screen system can better generate turbulence in the same location as the real inlet.
4. Reynolds number changes had little effect on the ability of the ADG system to match a desired pattern. RMSE varied no more than 0.4 percent, while DIST1 varied no more than 1.6 percent, both within the repeatability of the ADG system.
5. When screen patterns and ADG system patterns matched within 3 percent RMSE, there was little difference in engine surge pressure ratio (2.6 to -2.3 percent). Larger deviations in engine stability occurred for patterns with larger match errors. These deviations can be minimized by using empirical distortion corrections. However, there still exist small differences in engine stability.
6. The stability of the ADG system patterns was excellent. Changes in airflow up to 9 percent

caused less than 1 percent change in distortion. This allows patterns to be set with the engine on its normal operating, and held while the engine is surged.

7. The repeatability of the ADG system patterns was good. Patterns repeated at various times during the investigation repeated within ± 2 percent overall error.
8. The ADG system produced a specified inlet distortion pattern within two minutes after command. The pattern set time demonstrates the increased flexibility of the ADG system as compared with distortion screens.

The current ADG system has been shown to be a useful tool for turbine engine testing, but with a somewhat limited range in quantity of airflow to the engine, and severity of pressure gradients. Presently, the system can best produce patterns with moderate total-pressure gradients and fairly high turbulence.

Further investigation is needed to determine the optimum axial location of the airjet assembly with regard to the engine face. Steeper pressure gradients can be produced with the assembly near the engine face, but this will also increase the turbulence at the engine face. One way to make use of this trade-off might be to have the ADG assembly variable in its axial location.

In addition, the number and spacing of the airjets in the assembly should be investigated. Including any more jets than absolutely necessary will only complicate the ADG system control, but increasing the number of jets will allow more precise control of patterns.

Finally, the size of the individual nozzles should be considered. Optimizing the size of the nozzles will allow minimal use of secondary air.

Optimizing these aspects of the ADG system should lead to an engine testing tool that can be used over a broad range of simulated flight conditions.

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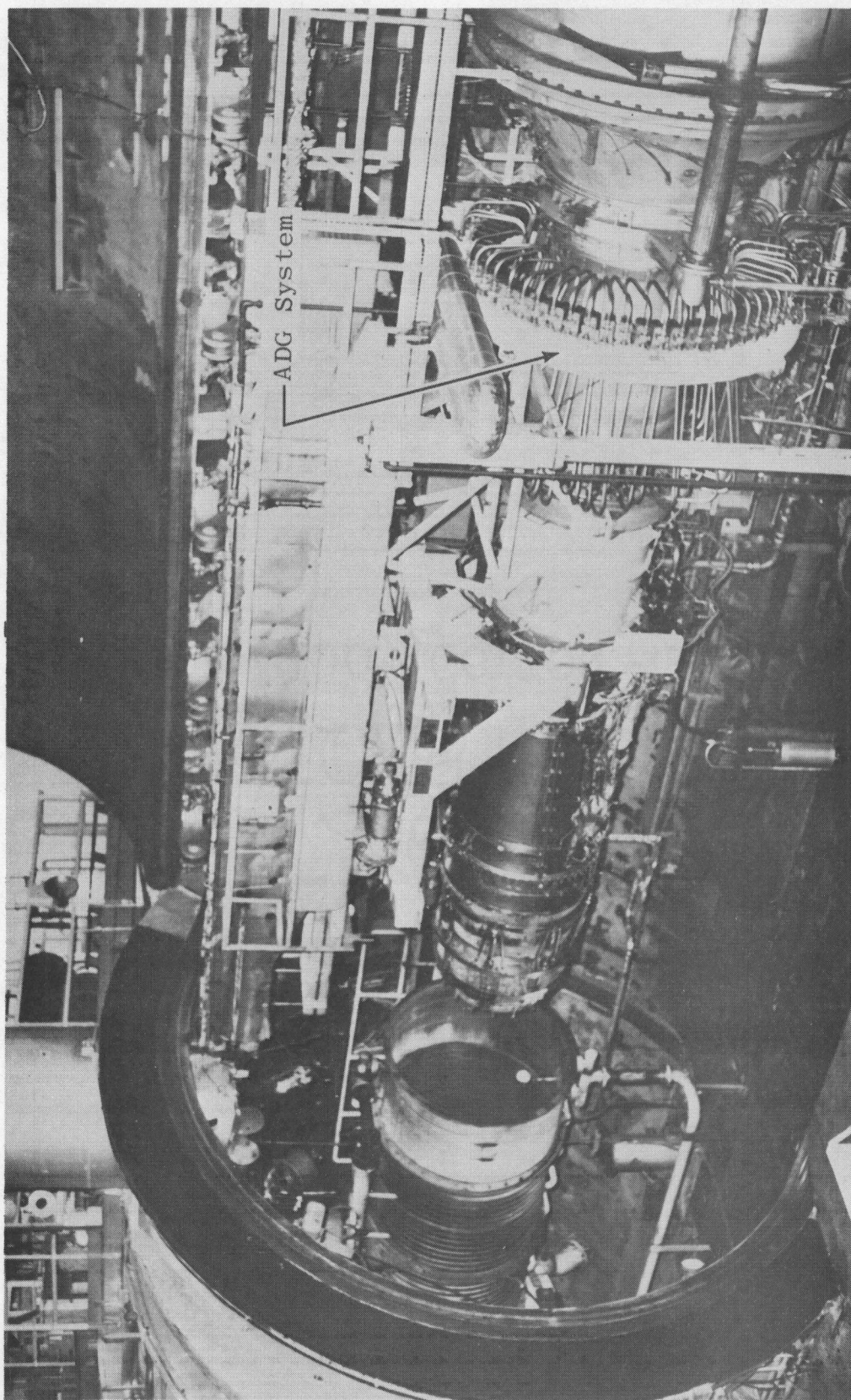
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APPENDIXES

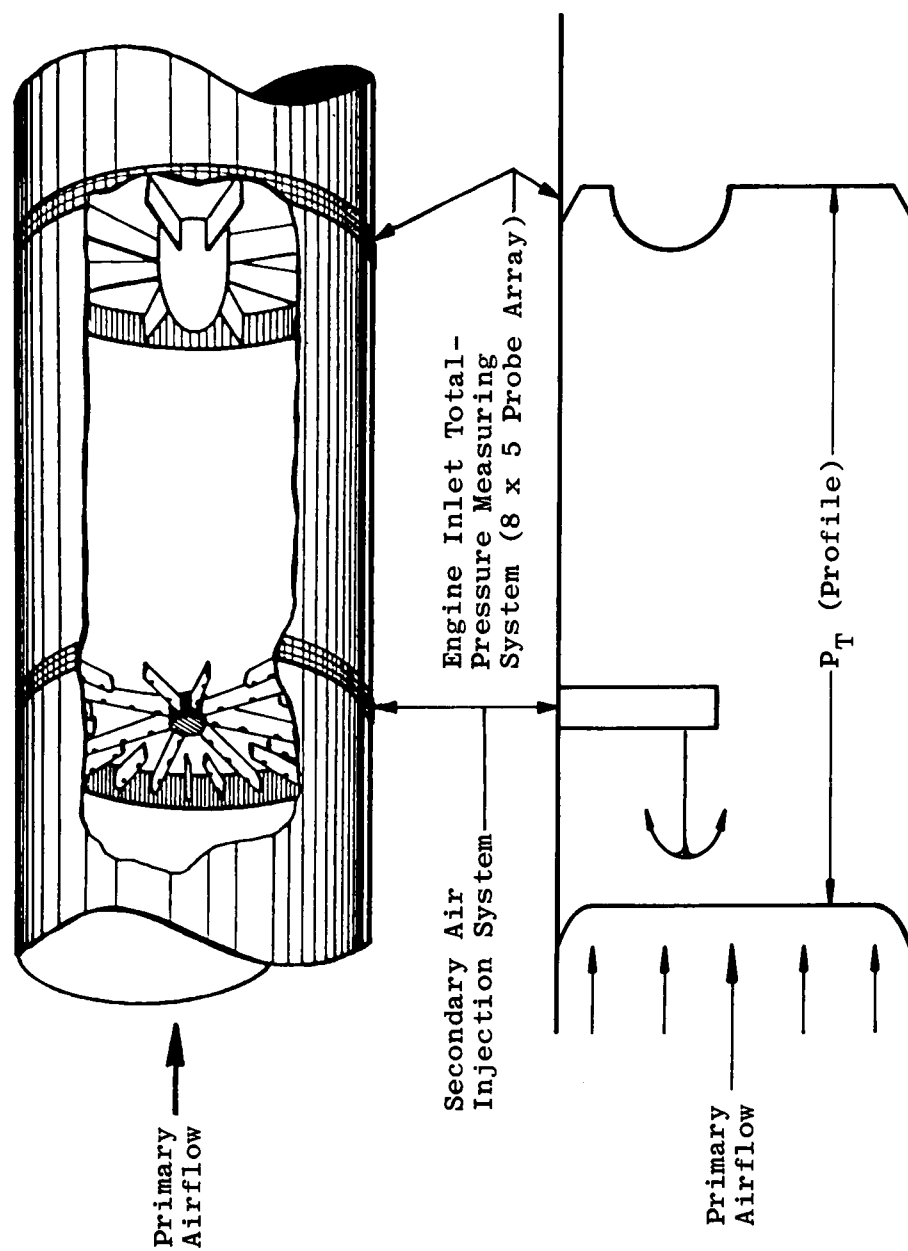
APPENDIX A

FIGURES



a. F101 Engine/ADG System Installed in Test Cell

Figure 1. Airjet distortion generator system.



b. Primary and Secondary Airflow

Figure 1 (Continued)

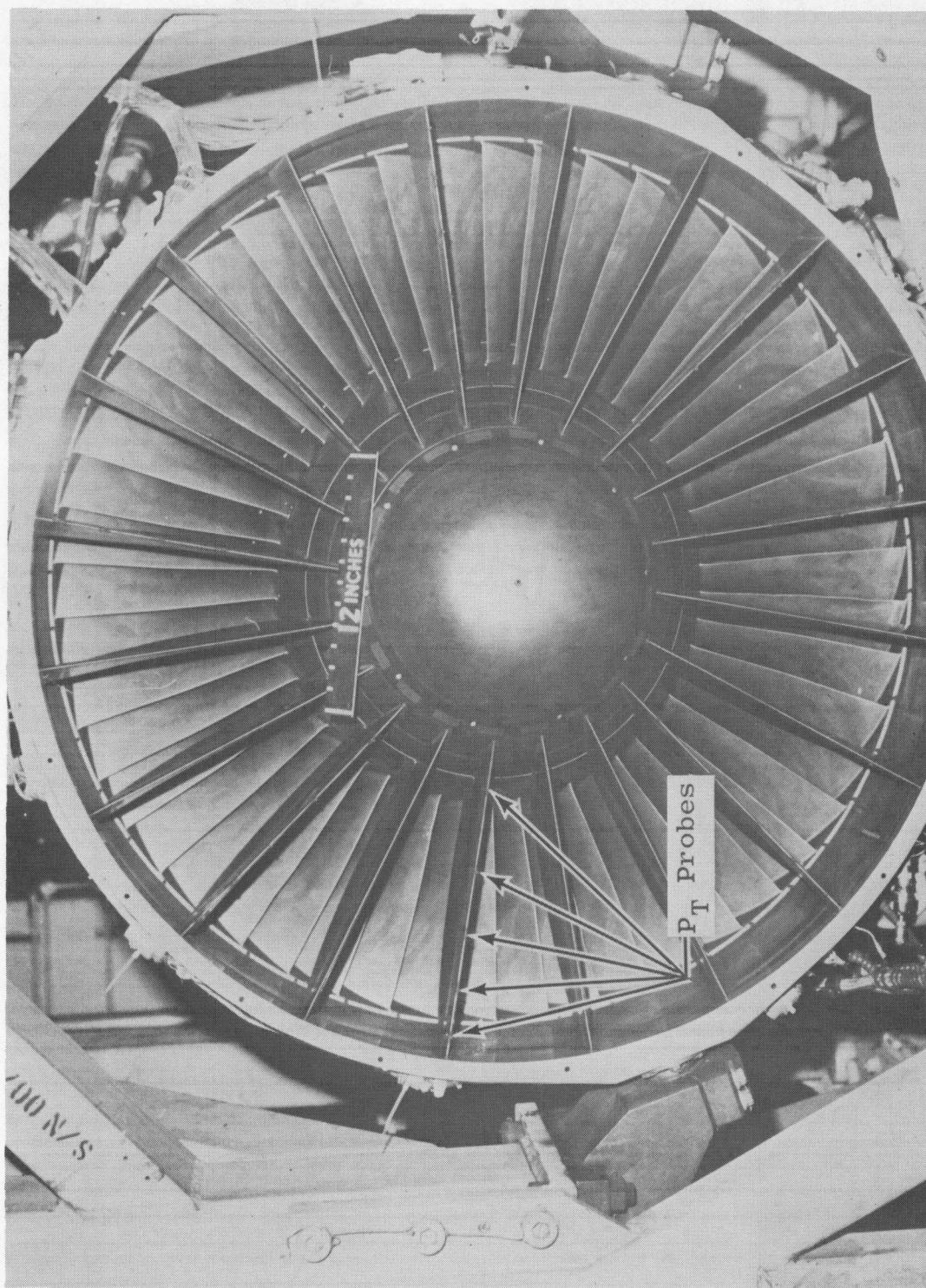
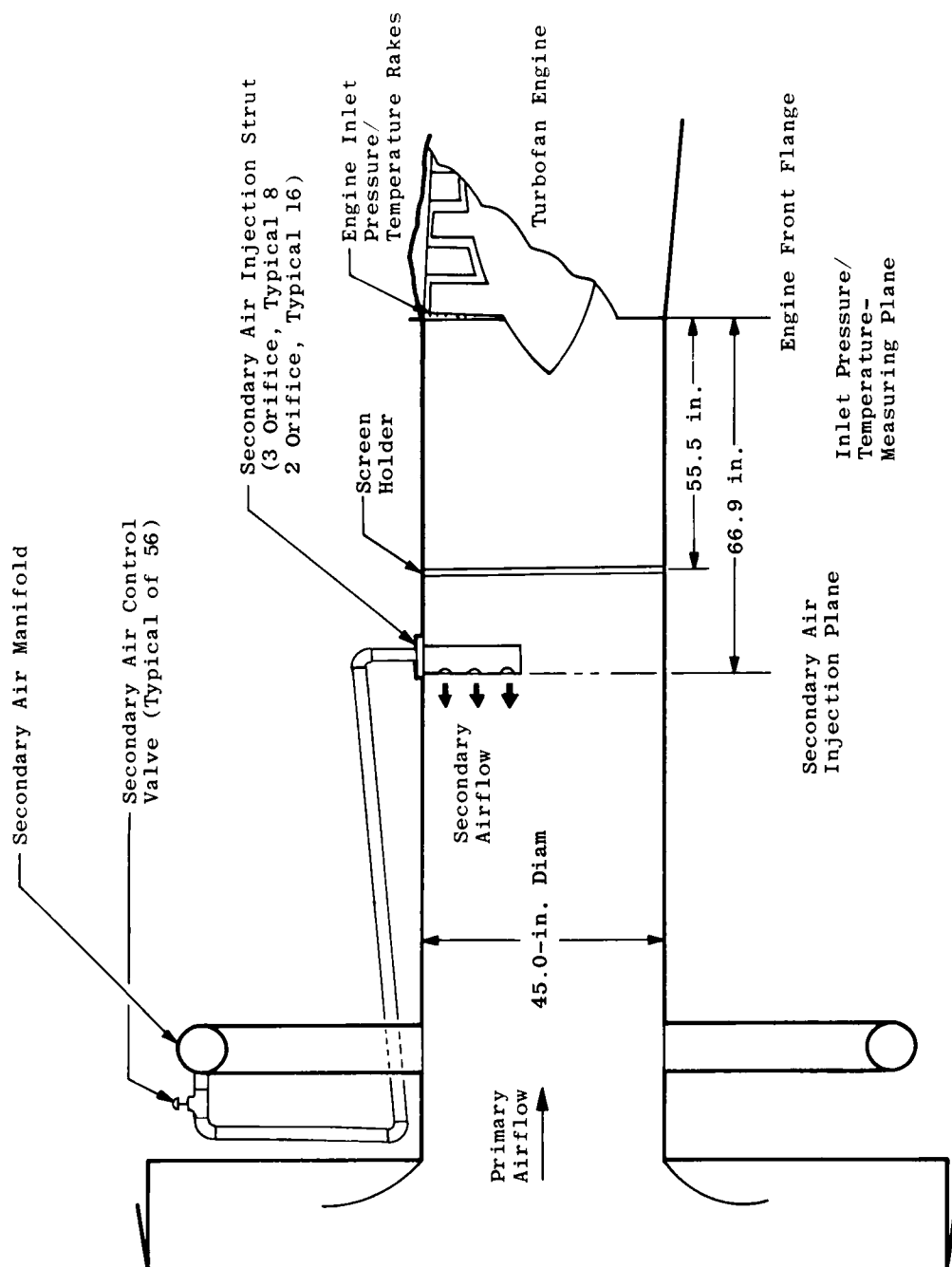
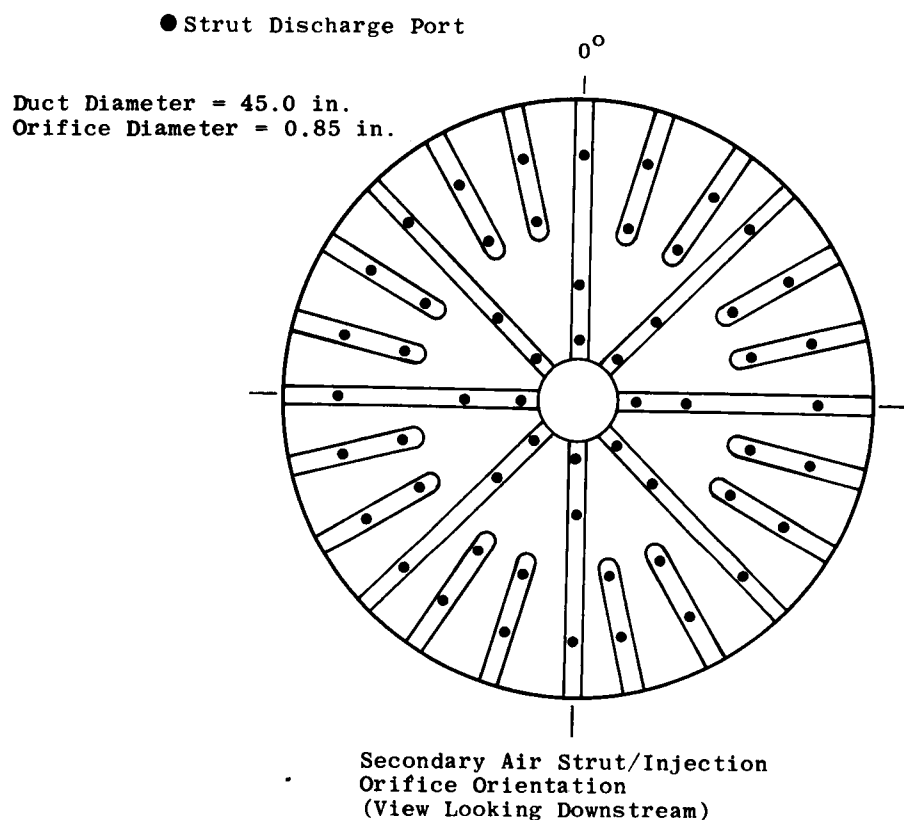
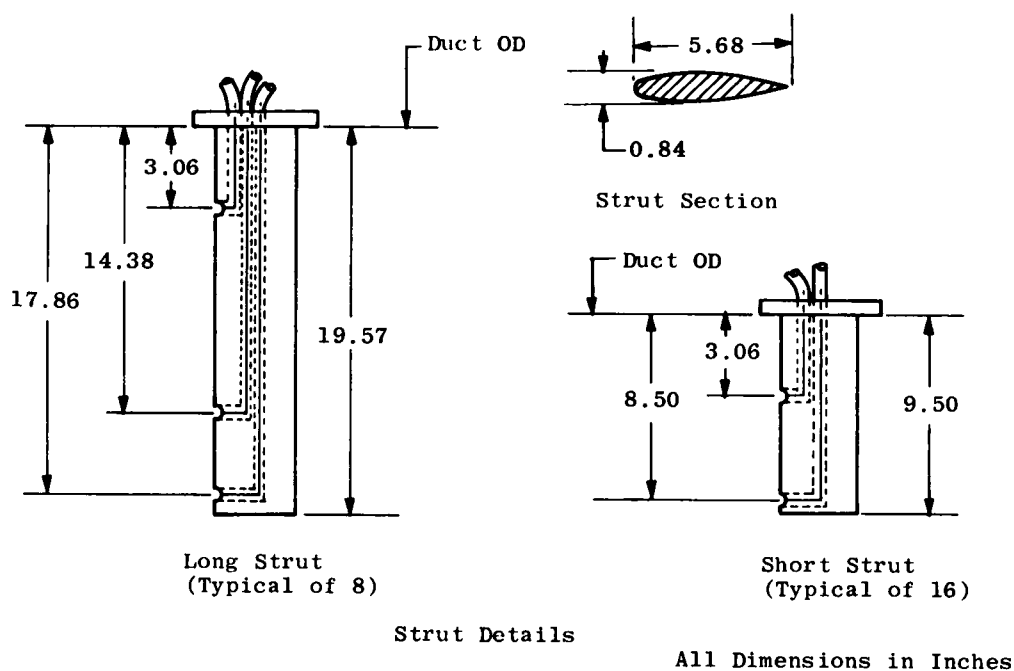


Figure 2. Engine front frame showing total-pressure probes.

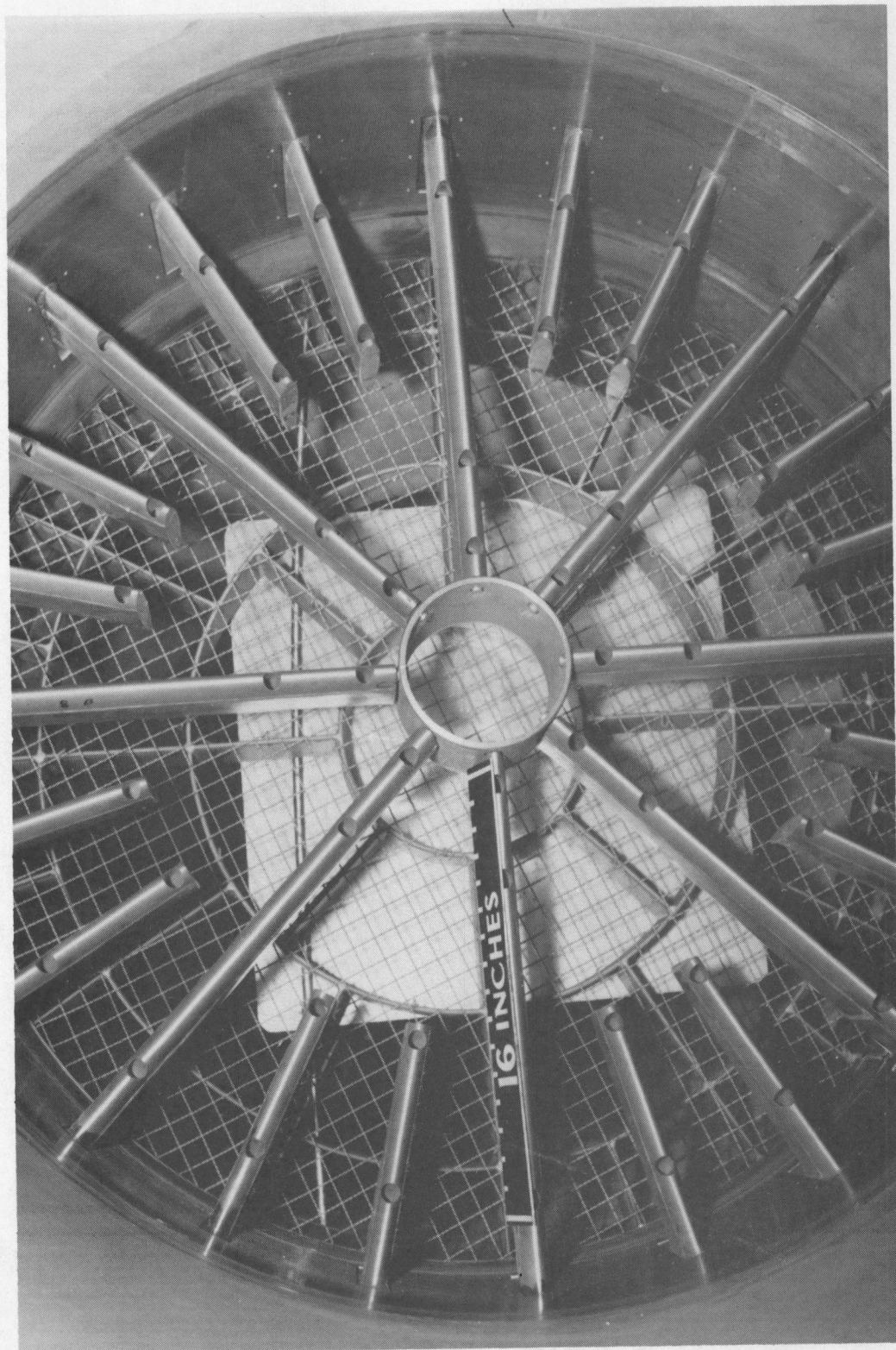


a. Airjet Distortion Generator System Schematic

Figure 3. Airjet assembly.

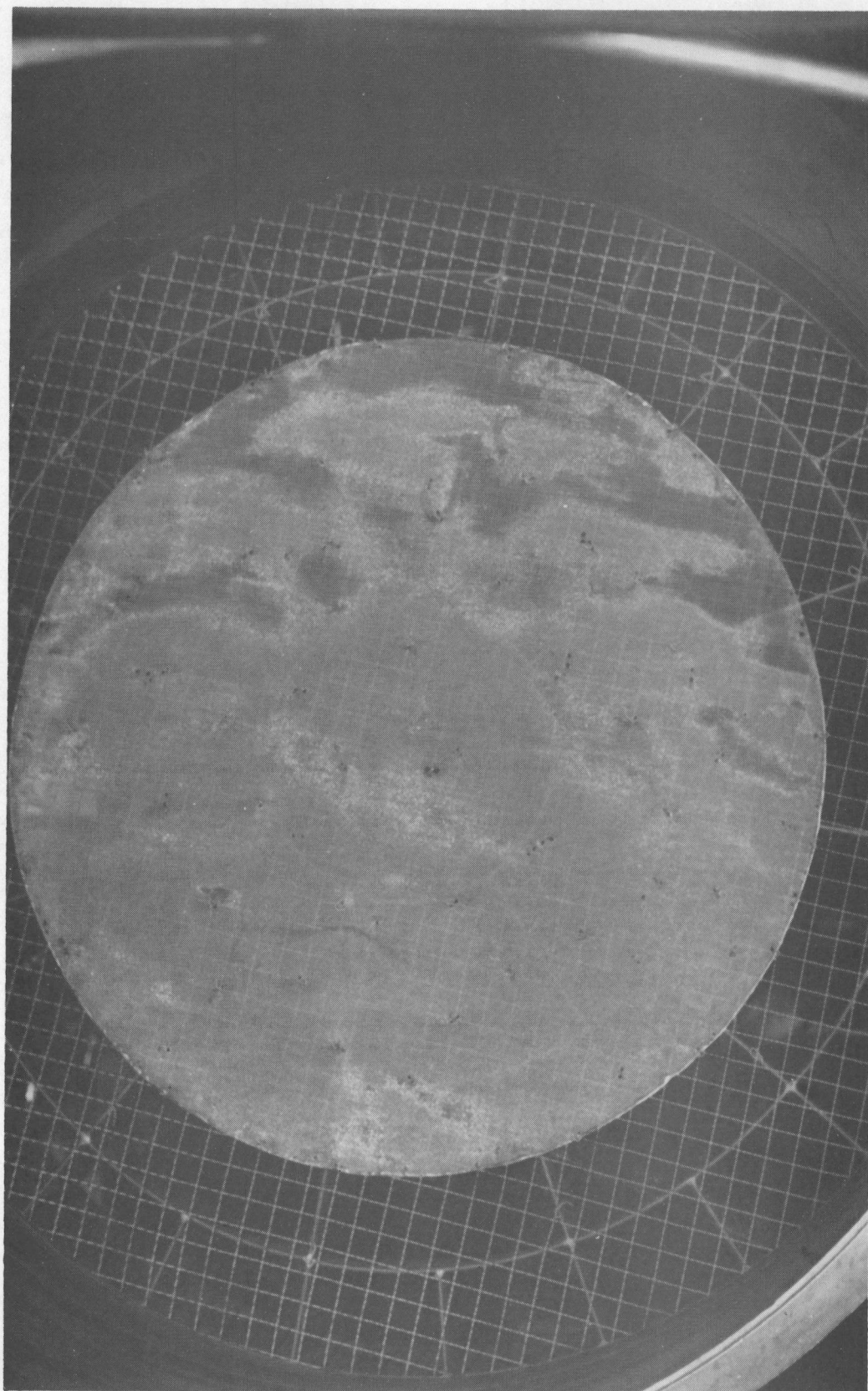


b. Air Injection Assembly Struts
Figure 3 (Continued)



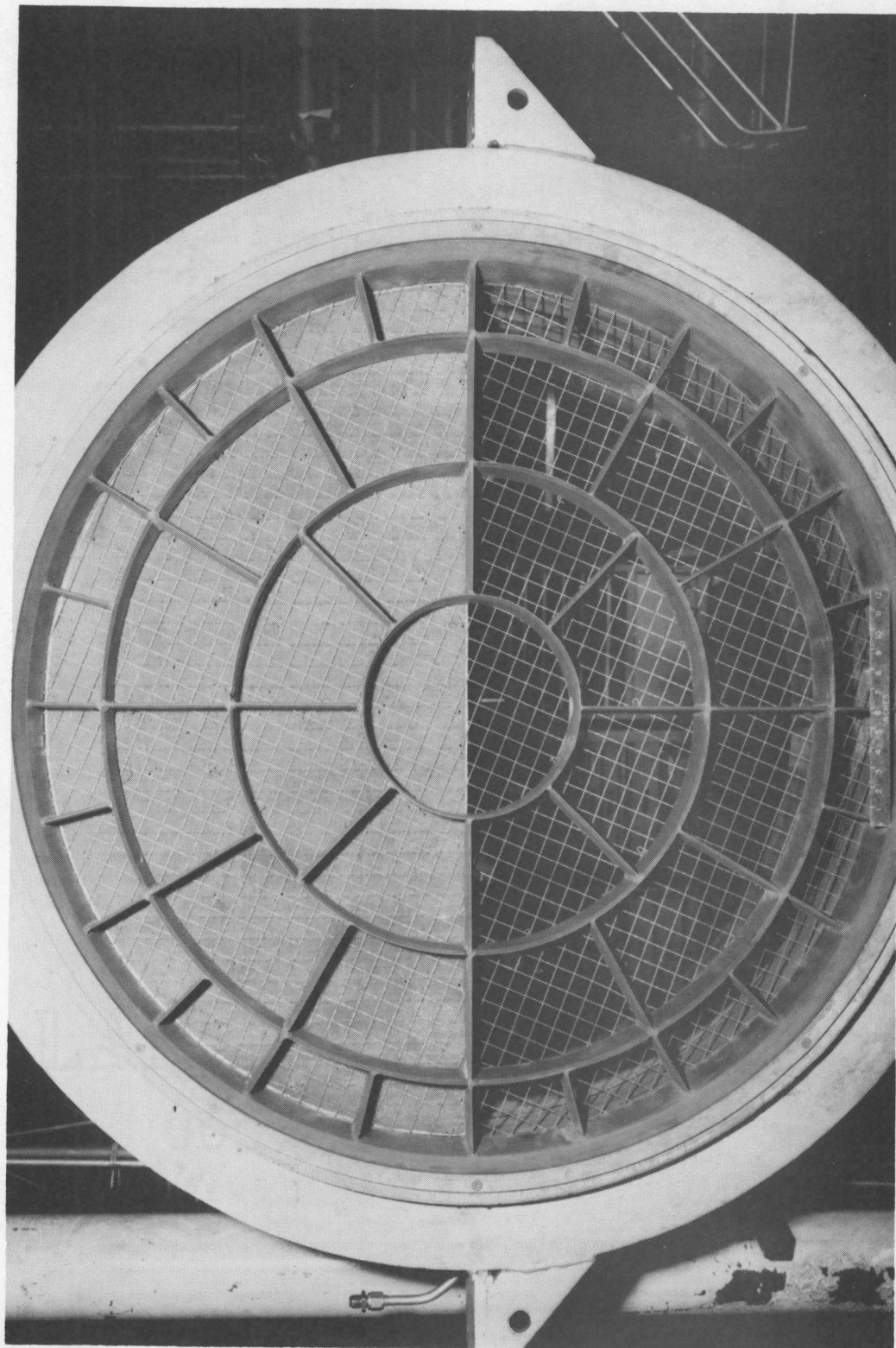
c. Airjet Assembly Installed

Figure 3 (Continued)



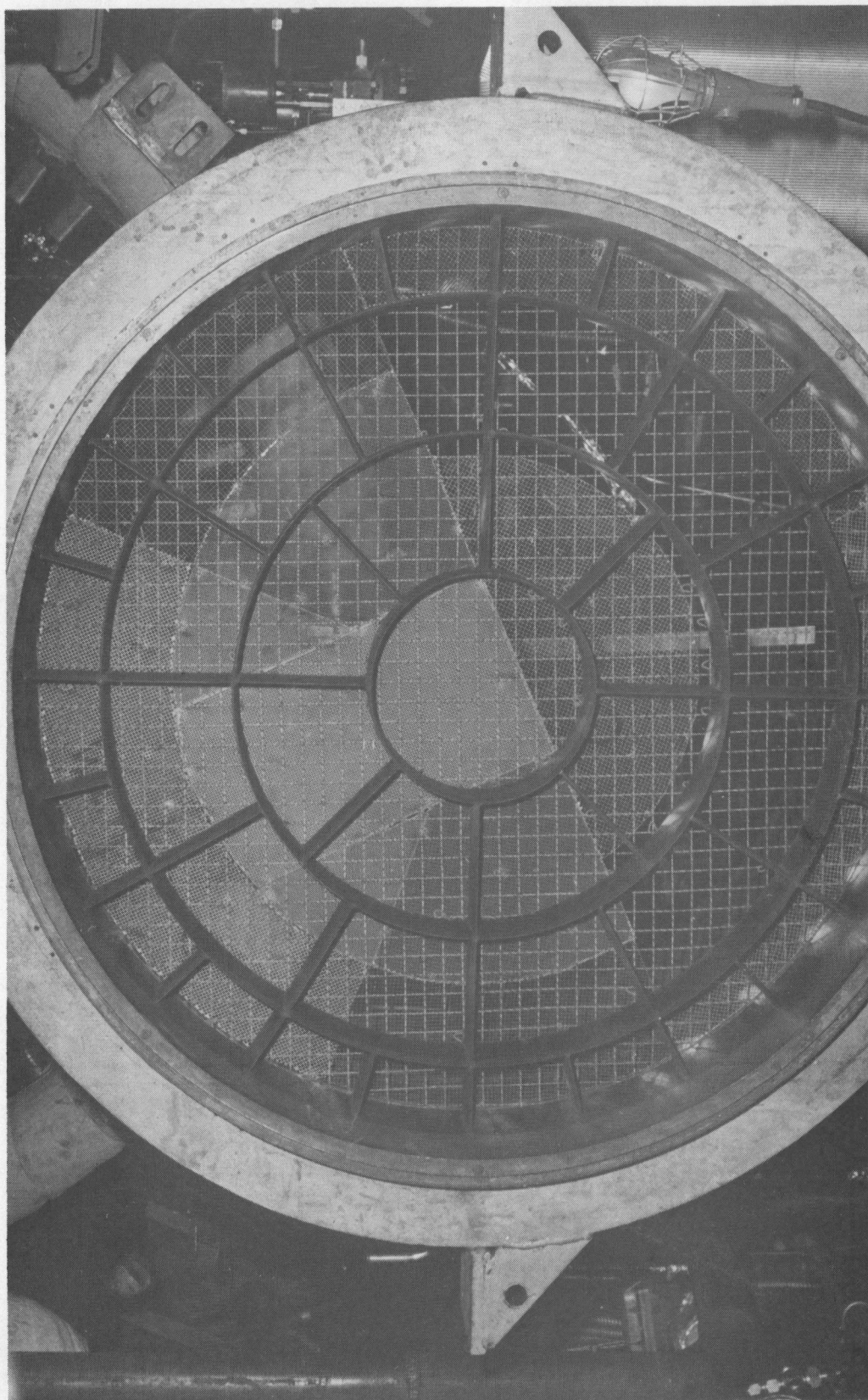
a. 50 Percent Hub Radial Screen No. 141

Figure 4. Inlet distortion screens.



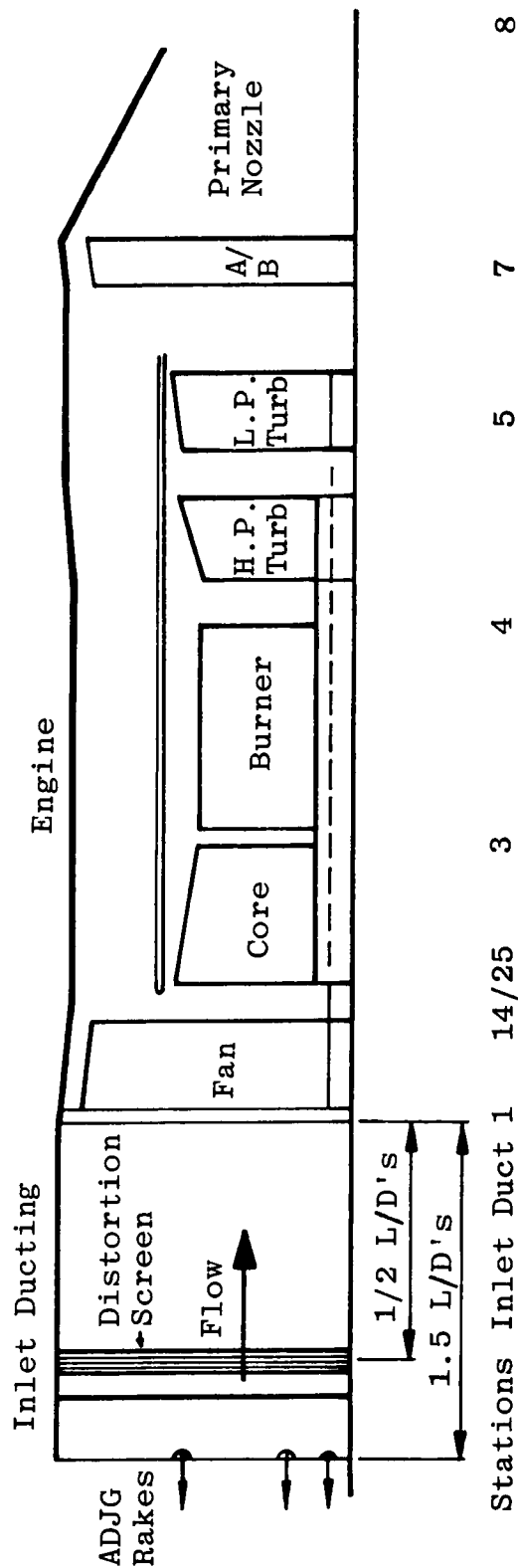
b. 180-deg, 1/rev Screen No. 106

Figure 4 (Continued)



c. F101 Specification Screen No. 354.7M

Figure 4 (Continued)



Total Measurements		990
Station 1	40	S.S. Pressures (Scanner Valve)
	40	Transient Pressures (Close-Couple Transducers)
	40	Dynamic Pressures (Kulites and ZOC Systems)
	<u>120</u>	Total @ Station 1
Station 14/25	84	S.S. Pressures
	64	Transient Pressures
	40	Dynamic Pressures
	80	Total Temperatures
	<u>268</u>	@ Station 14/25

Figure 5. Engine fan and compressor instrumentation.

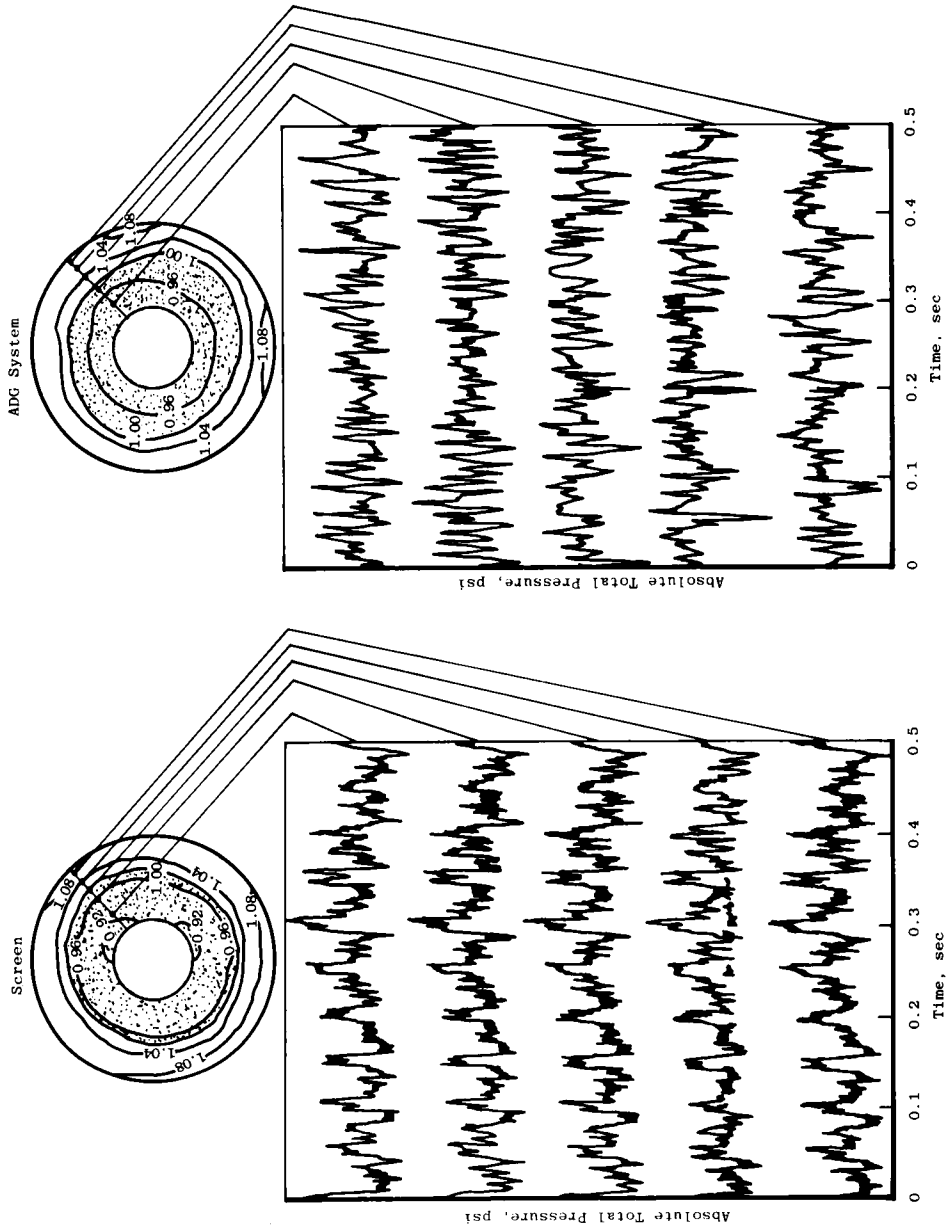


Figure 6. Variation of total pressure for screen and ADG system (50 percent hub radial pattern).

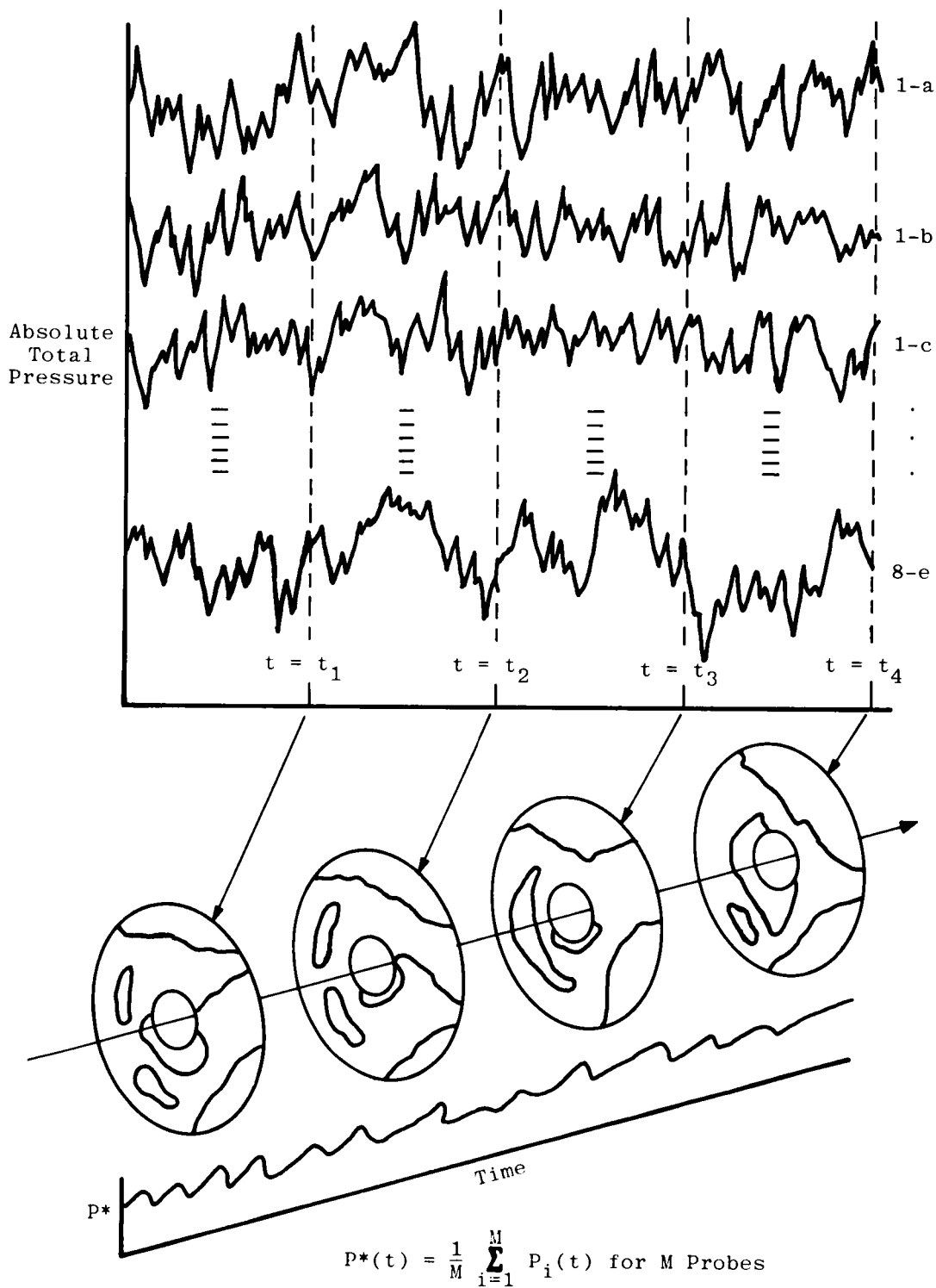
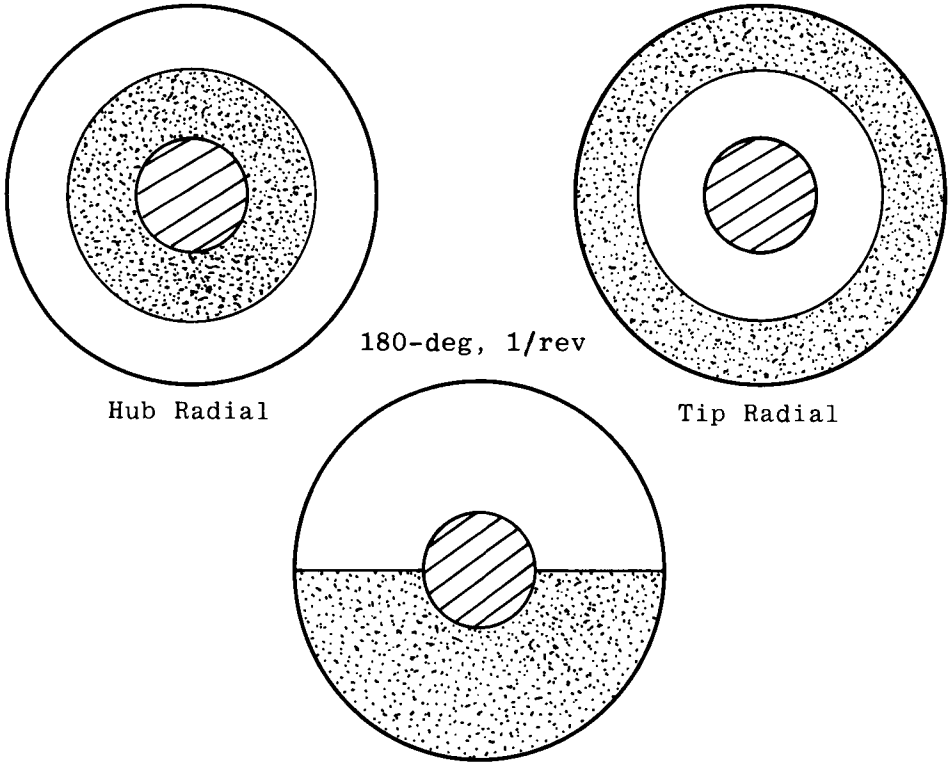
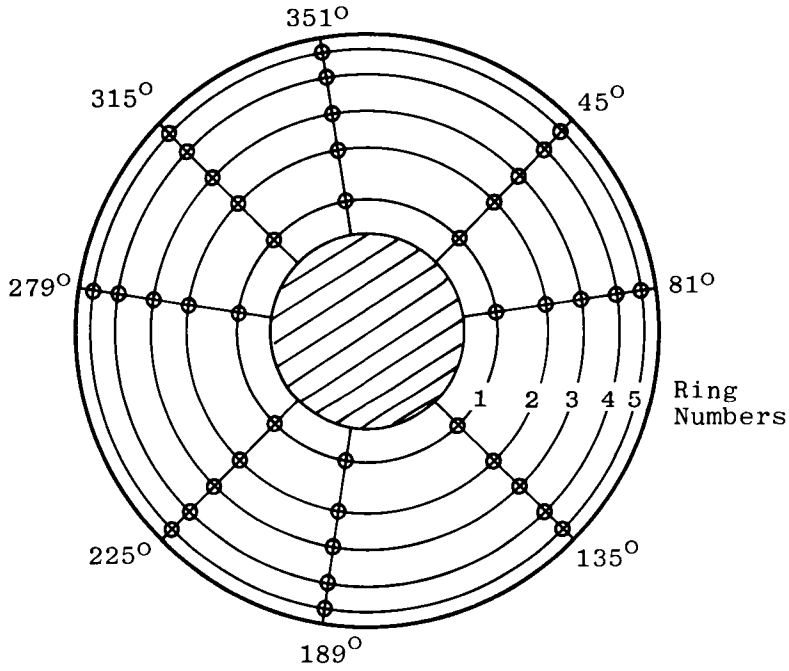


Figure 7. Contour map representation of absolute total-pressure variation.



a. Examples of Three Classical Patterns
(Shaded Area Represents Low Total Pressure)



b. Locations of Total Pressure Probes;
Five Rings, Eight Rakes

Figure 8. Total-pressure distribution for classical patterns with measurement locations.

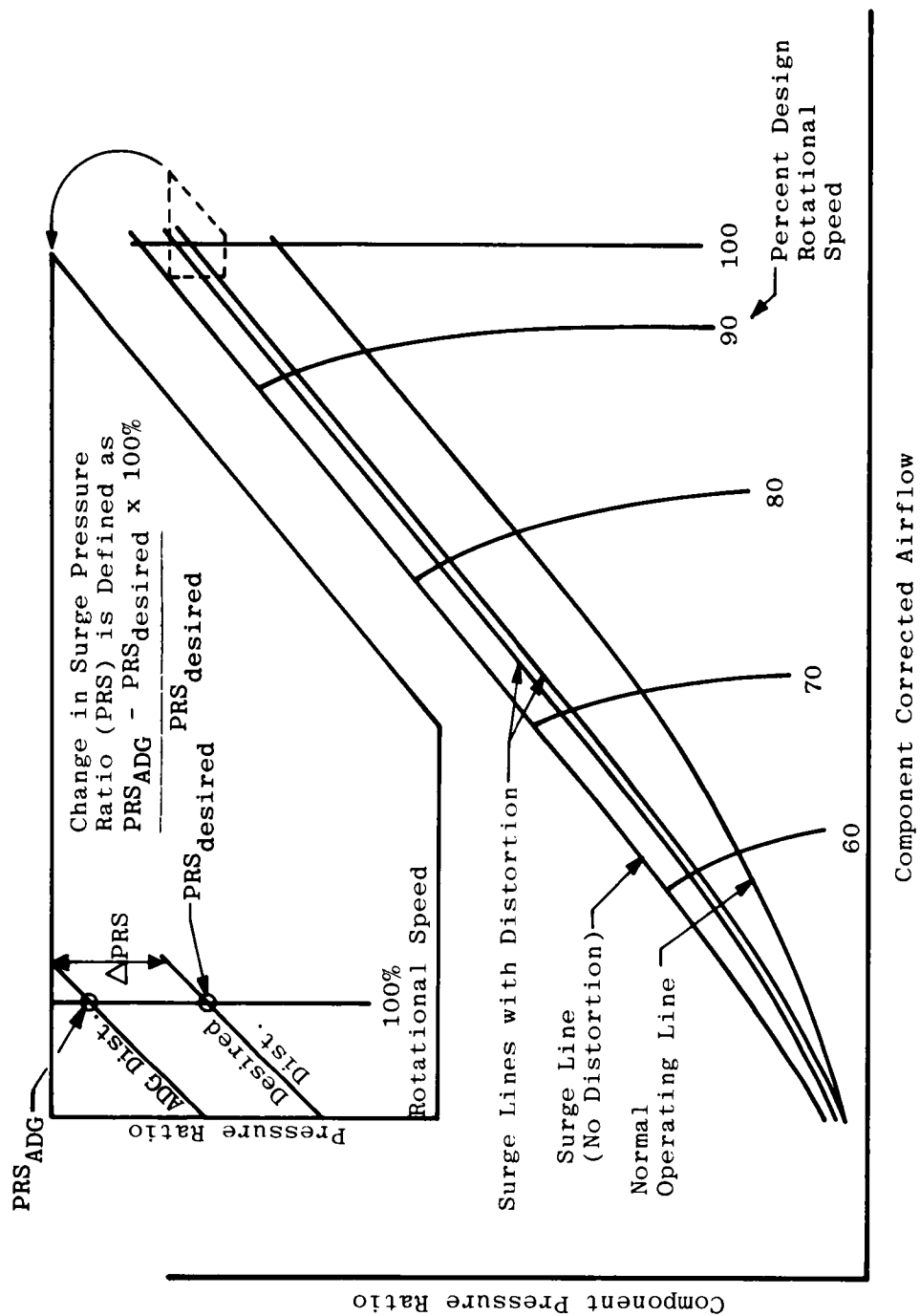


Figure 9. Typical component map.

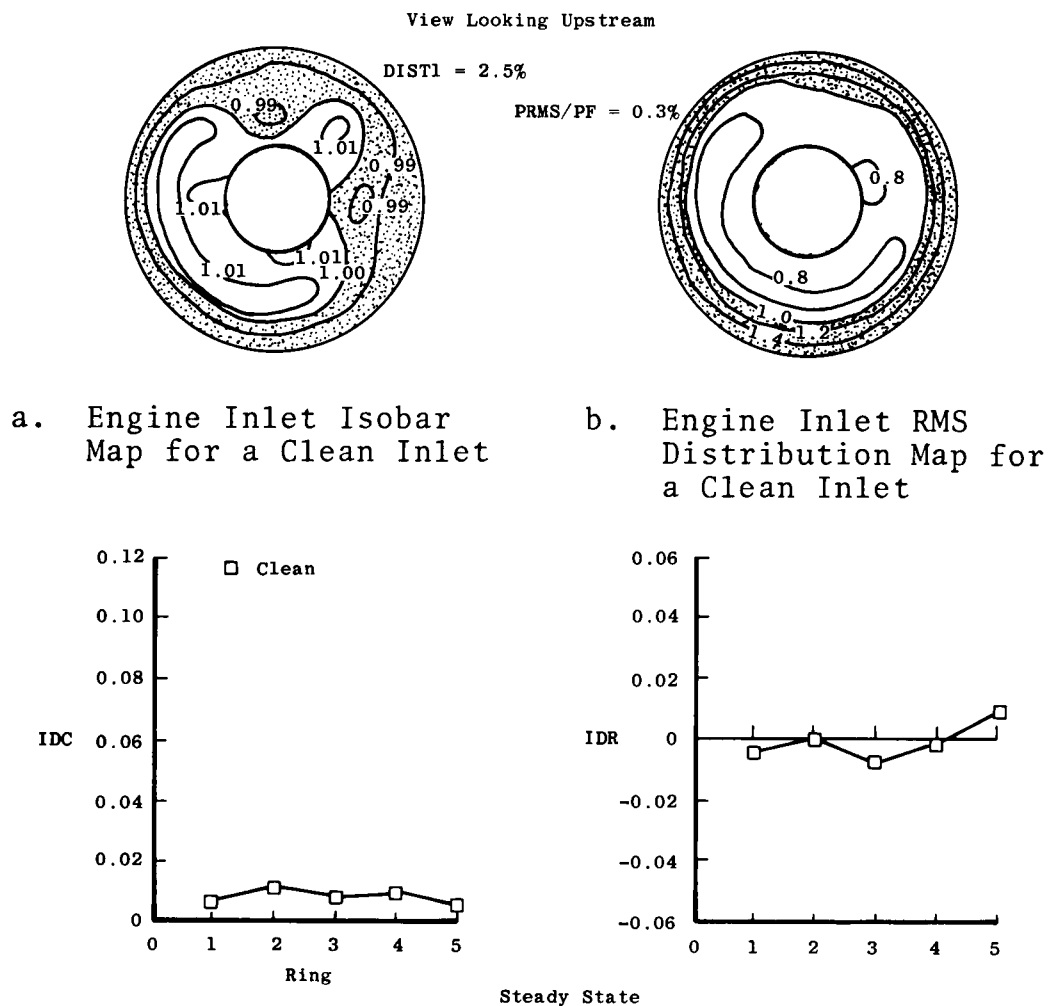
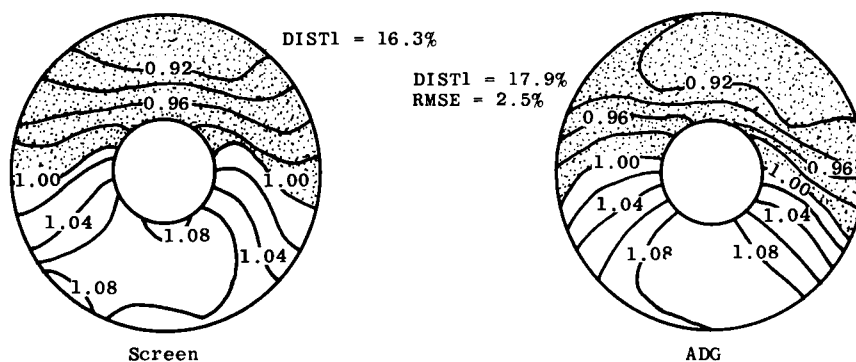
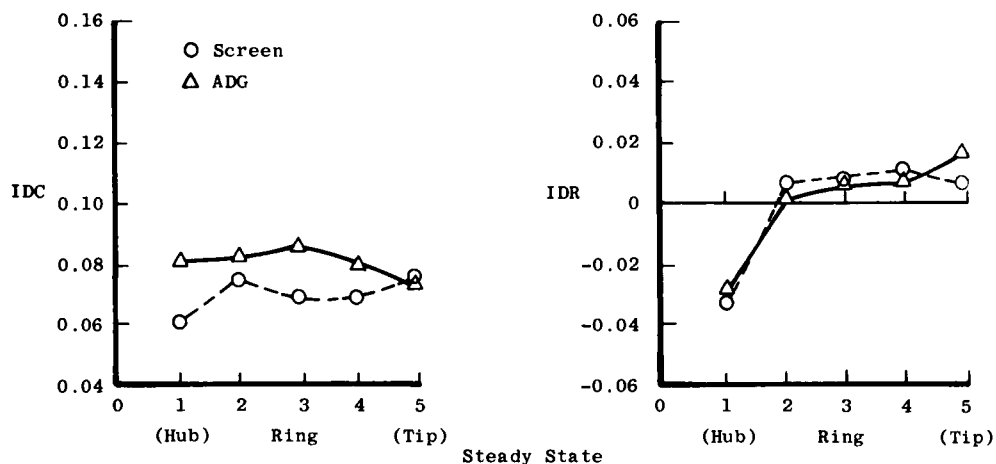


Figure 10. Steady-state and dynamic distortion for a clean inlet.

View Looking Upstream



a. Engine Inlet Isobar Maps for Screen and ADG System Distortion



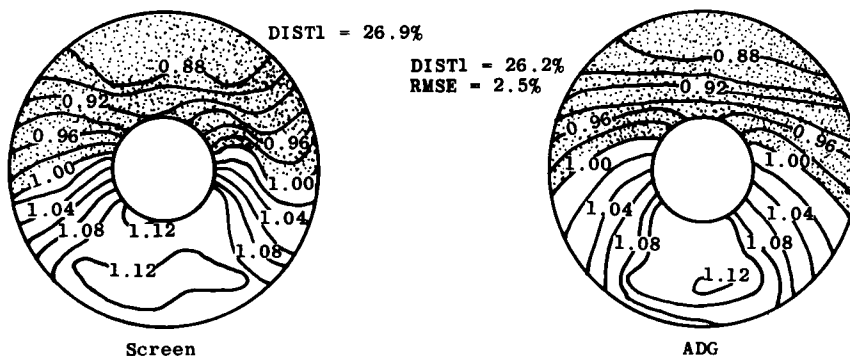
b. Distortion Indices for Screen and ADG System Distortion

Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.986	0.984	0.904	0.916	0.907	0.909	0.910	0.918	0.900	0.912
81	1.083	1.033	0.992	0.998	0.943	0.970	0.958	0.952	0.984	0.934
135	1.099	1.082	1.098	1.077	1.101	1.085	1.089	1.089	1.087	1.093
189	1.109	1.087	1.085	1.095	1.099	1.087	1.091	1.089	1.088	1.066
225	1.093	1.090	1.084	1.064	1.101	1.066	1.085	1.070	1.086	1.062
279	1.021	1.007	0.949	0.978	0.954	0.972	0.948	0.954	0.963	0.930
315	0.969	0.982	0.902	0.916	0.911	0.909	0.900	0.913	0.903	0.928
351	0.945	0.949	0.897	0.916	0.911	0.923	0.904	0.923	0.907	0.913

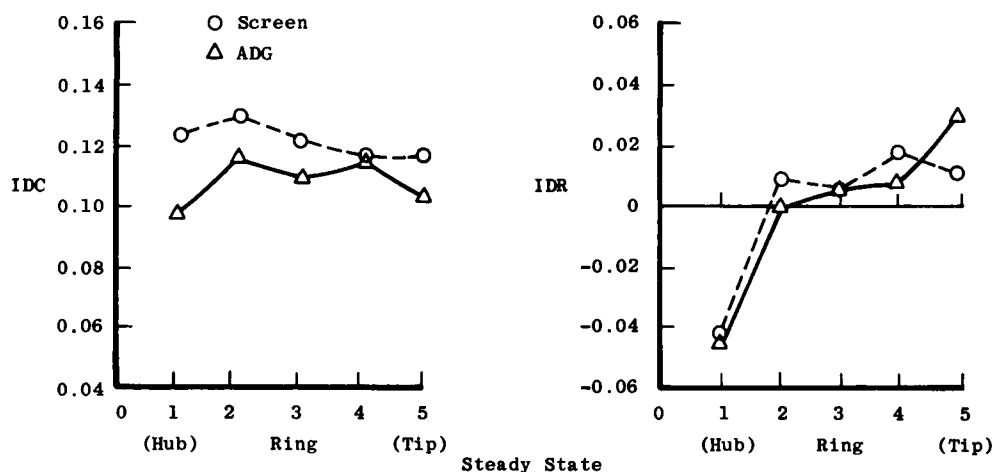
c. Individual Normalized Pressures at 40 Spatial Locations

Figure 11. Steady-state distortion comparison for 180-deg, 1/rev pattern No. 2 (low-speed fan surge).

View Looking Upstream



a. Engine Inlet Isobar Maps for Screen and ADG System Distortion



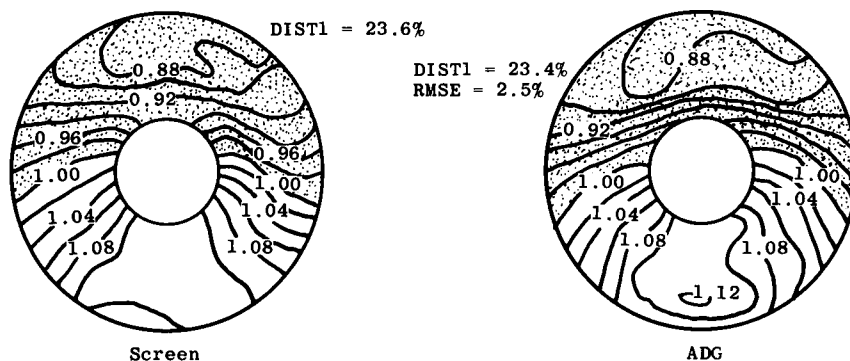
b. Distortion Indices for Screen and ADG System Distortion

Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.990	0.988	0.883	0.906	0.883	0.906	0.883	0.895	0.870	0.873
81	1.099	1.062	0.984	1.004	0.932	0.985	0.942	0.960	0.973	0.933
135	1.113	1.110	1.111	1.089	1.128	1.090	1.110	1.113	1.119	1.093
189	1.115	1.109	1.115	1.115	1.126	1.114	1.120	1.122	0.973	1.075
225	1.116	1.109	1.093	1.070	1.122	1.078	1.094	1.104	1.111	1.062
279	1.022	1.031	0.963	0.990	0.972	0.961	0.926	0.933	0.933	0.926
315	0.935	0.987	0.860	0.907	0.873	0.883	0.865	0.879	0.879	0.887
351	0.918	0.949	0.864	0.885	0.875	0.882	0.869	0.877	0.872	0.865

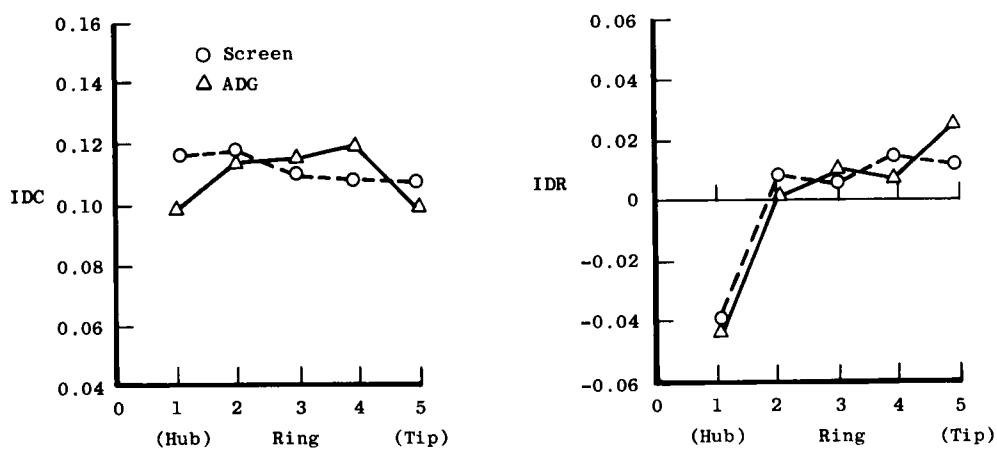
c. Individual Normalized Pressures at 40 Spatial Locations

Figure 12. Steady-state distortion comparison for 180-deg, 1/rev pattern No. 1 (high-speed fan surge).

View Looking Upstream



a. Engine Inlet Isobar Maps for Screen and ADG System Distortion

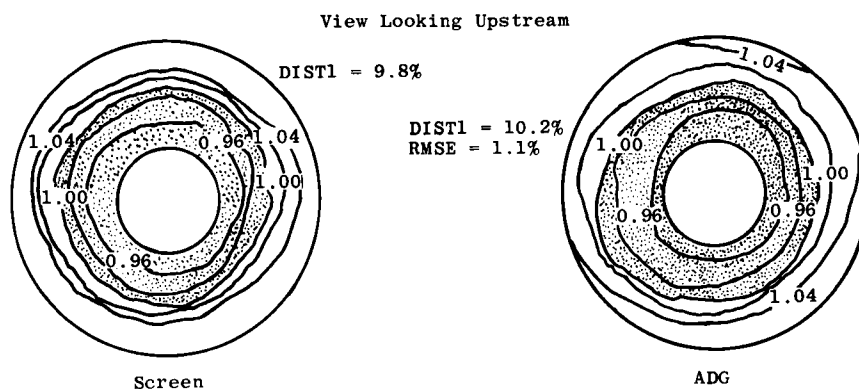


b. Distortion Indices for Screen and ADG System Distortion

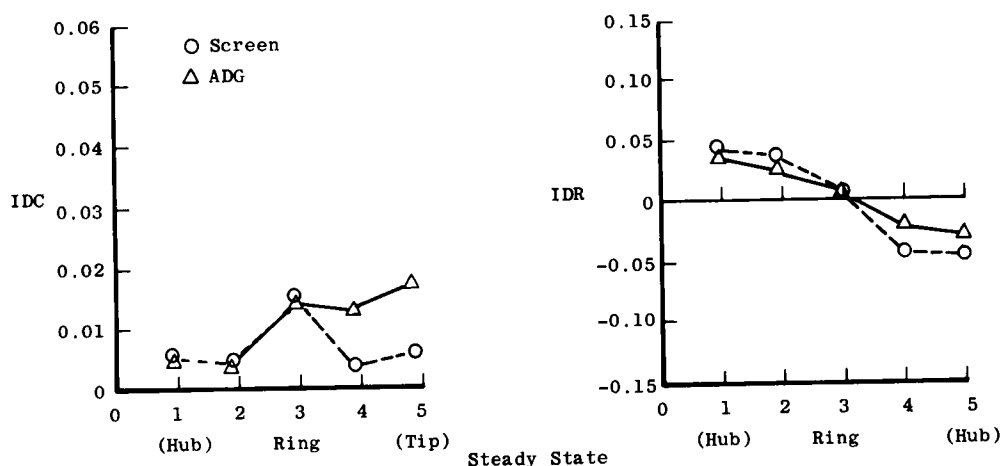
Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.984	1.001	0.887	0.898	0.888	0.882	0.900	0.897	0.880	0.880
81	1.095	1.063	0.992	1.010	0.943	0.978	0.950	0.974	0.971	0.944
135	1.100	1.105	1.106	1.085	1.116	1.097	1.101	1.103	1.105	1.073
189	1.105	1.111	1.104	1.106	1.112	1.110	1.105	1.125	1.091	1.098
225	1.108	1.115	1.083	1.082	1.109	1.085	1.083	1.097	1.098	1.079
279	1.021	1.012	0.967	0.989	0.976	0.958	0.938	0.946	0.944	0.921
315	0.951	0.975	0.876	0.888	0.888	0.873	0.876	0.873	0.892	0.891
351	0.923	0.946	0.874	0.882	0.886	0.890	0.881	0.886	0.882	0.875

c. Individual Normalized Pressures at 40 Spatial Locations

Figure 13. Steady-state distortion comparison for 180-deg, 1/rev pattern No. 23 (core surge).



a. Engine Inlet Isobar Maps for Screen and ADG System Distortion

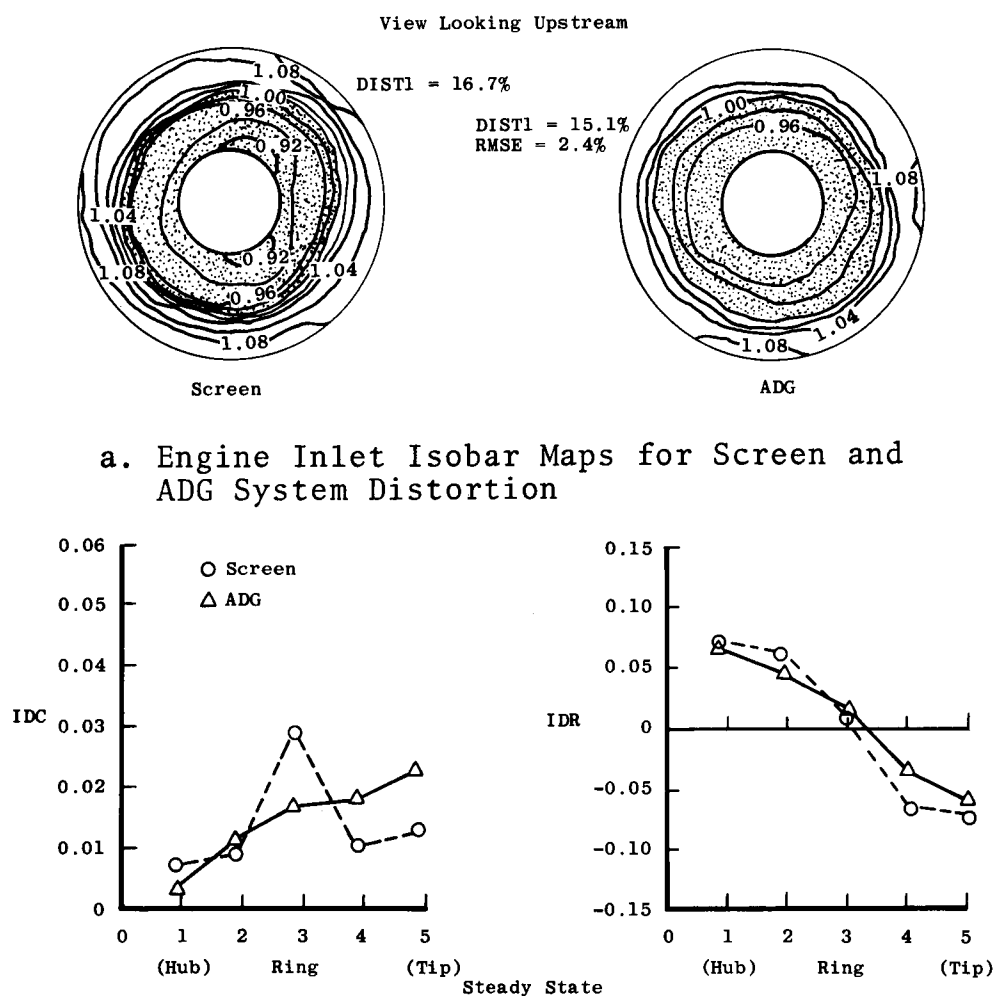


b. Distortion Indices for Screen and ADG System Distortion

Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.958	0.964	0.960	0.980	0.991	1.000	1.039	1.020	1.044	1.033
81	0.965	0.967	0.972	0.981	1.019	1.011	1.039	1.042	1.038	1.042
135	0.954	0.958	0.962	0.975	0.992	0.995	1.041	1.030	1.047	1.051
189	0.954	0.962	0.960	0.976	1.004	1.000	1.052	1.037	1.048	1.044
225	0.963	0.965	0.961	0.974	0.991	0.996	1.039	1.030	1.045	1.043
279	0.958	0.968	0.961	0.973	0.984	0.988	1.043	1.018	1.043	1.022
315	0.963	0.965	0.958	0.972	0.979	0.982	1.038	1.013	1.038	1.025
351	0.956	0.960	0.969	0.976	0.995	0.993	1.037	1.018	1.041	1.041

c. Individual Normalized Pressures at 40 Spatial Locations

Figure 14. Steady-state distortion comparison for 50 percent hub radial pattern No. 4 (low-speed fan surge).

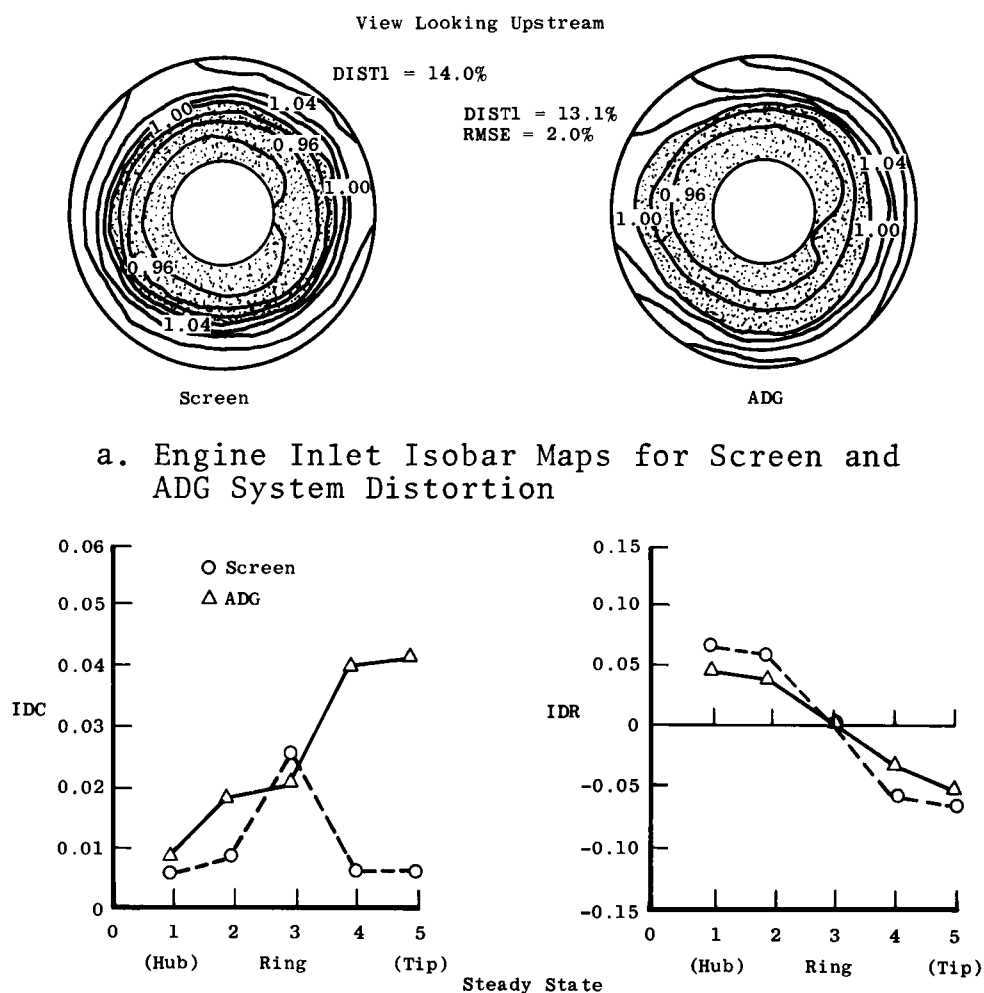


b. Distortion Indices for Screen and ADG System Distortion

Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.926	0.941	0.933	0.975	0.999	1.018	1.064	1.053	1.082	1.068
81	0.936	0.940	0.950	0.947	1.020	0.996	1.068	1.064	1.063	1.081
135	0.924	0.936	0.932	0.968	0.981	0.989	1.070	1.028	1.079	1.057
189	0.921	0.937	0.931	0.960	1.014	0.983	1.090	1.044	1.079	1.087
225	0.934	0.938	0.934	0.974	0.990	1.011	1.071	1.052	1.078	1.070
279	0.929	0.940	0.931	0.953	0.973	0.995	1.078	1.029	1.078	1.041
315	0.936	0.945	0.926	0.959	0.961	0.984	1.061	1.022	1.071	1.045
351	0.922	0.941	0.946	0.950	0.986	0.976	1.070	1.027	1.069	1.076

c. Individual Normalized Pressures at 40 Spatial Locations

Figure 15. Steady-state distortion comparison for 50 percent hub radial pattern No. 3 (high-speed fan surge).

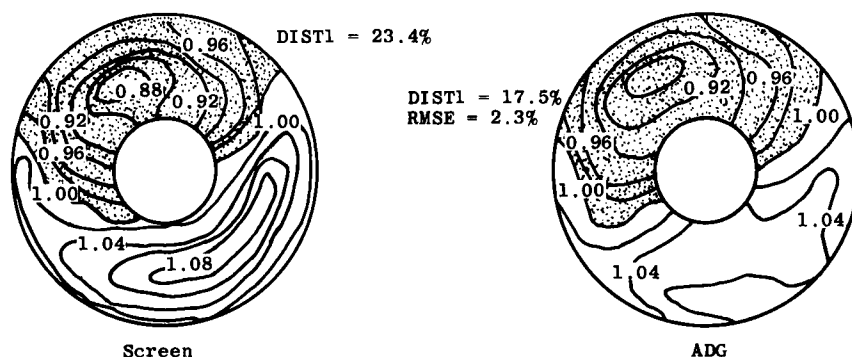


Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.939	1.058	0.943	0.975	1.000	1.011	1.049	1.058	1.064	1.071
81	0.948	0.948	0.957	0.975	1.028	1.015	1.053	1.063	1.052	1.062
135	0.934	0.968	0.946	0.965	0.994	0.994	1.057	1.035	1.064	1.052
189	0.934	0.946	0.942	0.964	1.011	1.011	1.074	1.062	1.066	1.076
225	0.947	0.943	0.944	0.954	0.995	0.995	1.054	1.042	1.063	1.051
279	0.937	0.950	0.943	0.946	0.981	0.984	1.057	0.997	1.061	1.010
315	0.946	0.957	0.938	0.964	0.973	0.978	1.050	1.001	1.054	1.016
351	0.937	0.947	0.957	0.960	0.998	0.990	1.053	1.040	1.055	1.061

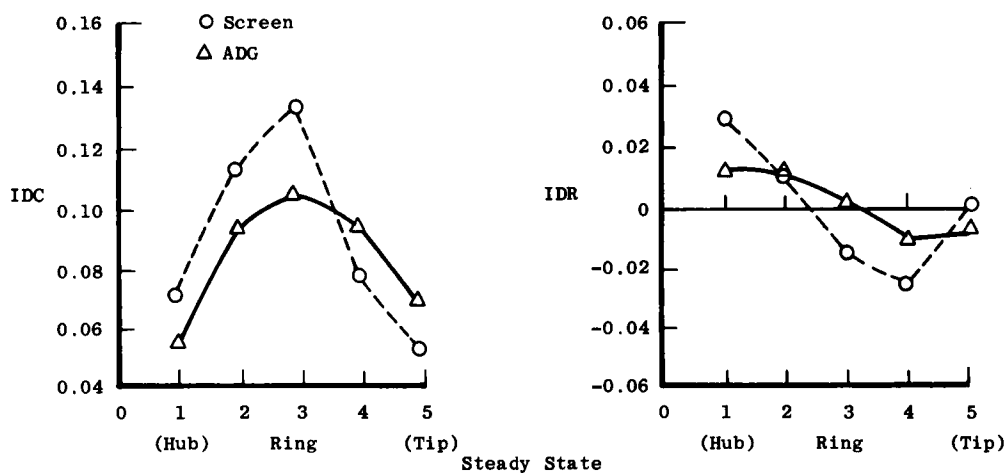
c. Individual Normalized Pressures at
40 Spatial Locations

Figure 16. Steady-state distortion comparison for 50 percent hub radial pattern No. 25 (core surge).

View Looking Upstream



a. Engine Inlet Isobar Maps for Screen and ADG System Distortion



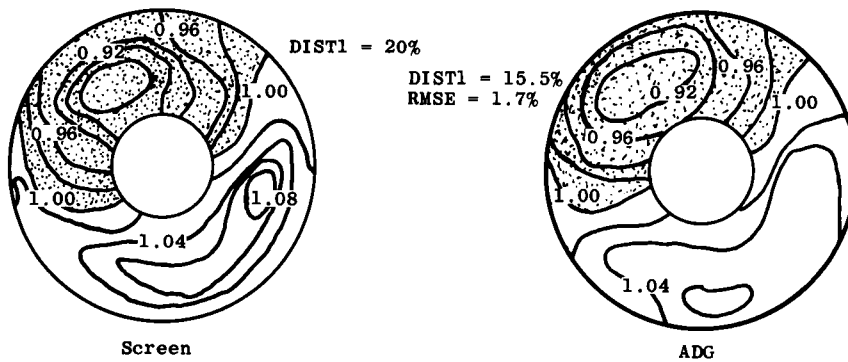
b. Distortion Indices for Screen and ADG System Distortion

Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.938	0.958	0.945	0.960	0.974	0.978	1.022	0.997	1.016	1.002
81	1.024	1.006	1.054	1.035	1.113	1.038	1.081	1.044	1.014	1.033
135	1.026	1.053	1.048	1.042	1.086	1.056	1.045	1.052	1.021	1.052
189	1.027	1.033	1.074	1.060	1.091	1.064	1.057	1.070	1.019	1.070
225	0.992	1.027	1.041	1.036	1.081	1.045	1.039	1.058	1.005	1.029
279	0.993	0.946	0.962	0.945	0.963	0.960	1.033	1.006	1.011	1.005
315	0.901	0.935	0.880	0.897	0.884	0.903	0.953	0.937	0.948	0.957
351	0.905	0.934	0.883	0.899	0.888	0.895	0.949	0.924	0.944	0.946

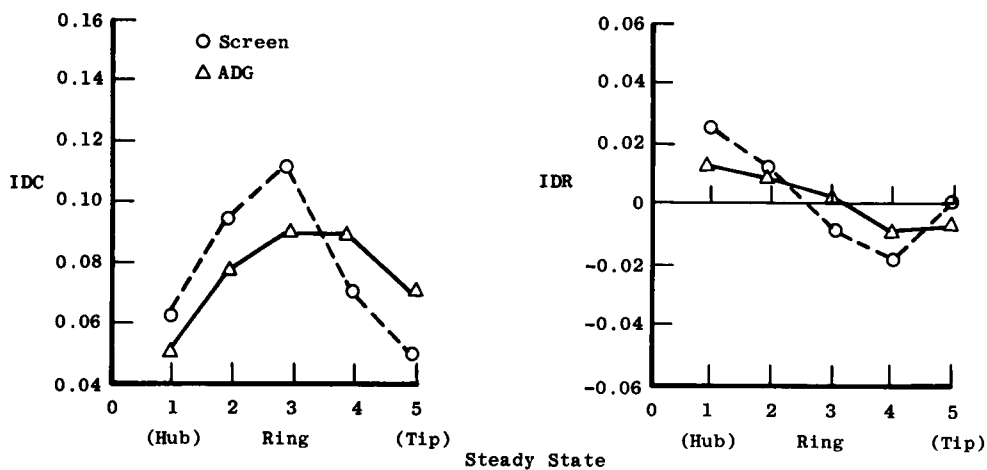
c. Individual Normalized Pressures at 40 Spatial Locations

Figure 17. Steady-state distortion comparison for F101 specification pattern No. 26 (high-speed fan surge).

View Looking Upstream



a. Engine Inlet Isobar Maps for Screen and ADG System Distortion

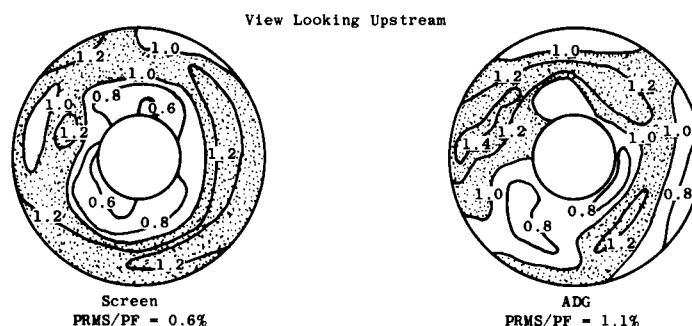


b. Distortion Indices for Screen and ADG System Distortion

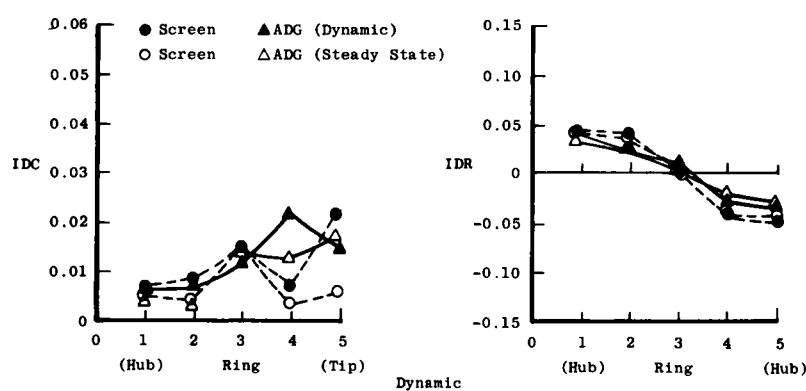
Rake Angle	Ring Number (Hub to Tip)									
	1		2		3		4		5	
	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG	Screen	ADG
45	0.947	0.964	0.955	0.965	0.974	0.975	1.020	0.990	1.012	0.995
81	1.019	0.996	1.051	1.027	1.096	1.036	1.066	1.039	1.014	1.031
135	1.024	1.032	1.042	1.046	1.073	1.046	1.040	1.049	1.018	1.056
189	1.023	1.033	1.063	1.055	1.076	1.059	1.050	1.057	1.018	1.038
225	0.998	1.032	1.035	1.038	1.069	1.046	1.031	1.053	1.004	1.028
279	0.943	0.958	0.965	0.963	0.968	1.095	1.027	1.002	1.010	1.001
315	0.912	0.947	0.897	0.915	0.901	0.917	0.961	0.943	0.955	0.959
351	0.914	0.944	0.900	0.918	0.901	0.912	0.957	0.929	0.951	0.945

c. Individual Normalized Pressures at 40 Spatial Locations

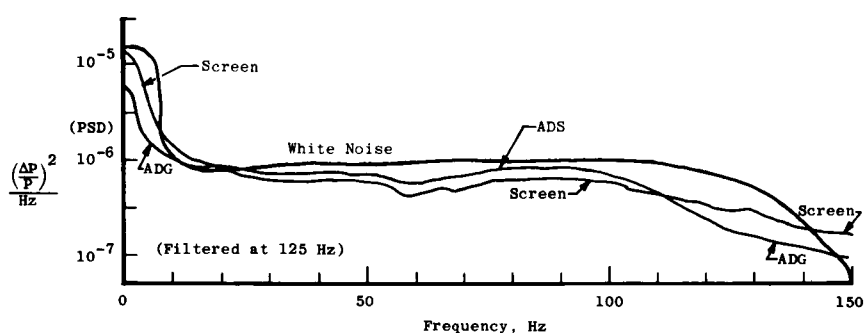
Figure 18. Steady-state distortion comparison for F101 specification pattern No. 27 (core surge).



a. Engine Inlet RMS Distribution Maps for Screen and ADG System Distortion



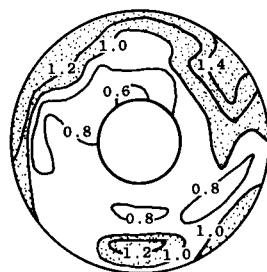
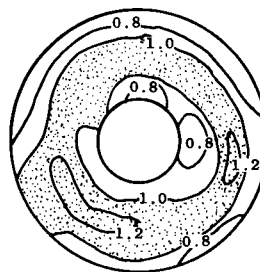
b. Distortion Indices for Screen and ADG System Distortion



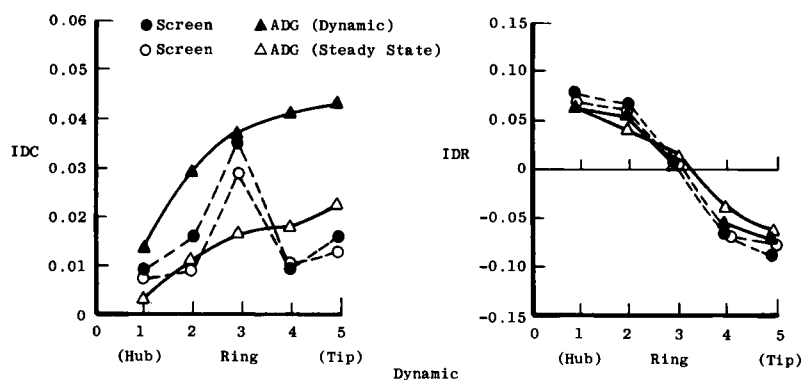
c. Power Spectral Density Characteristics for Screen and ADG System Distortion

Figure 19. Dynamic distortion comparison for 50 percent hub radial pattern No. 4 (low-speed fan surge).

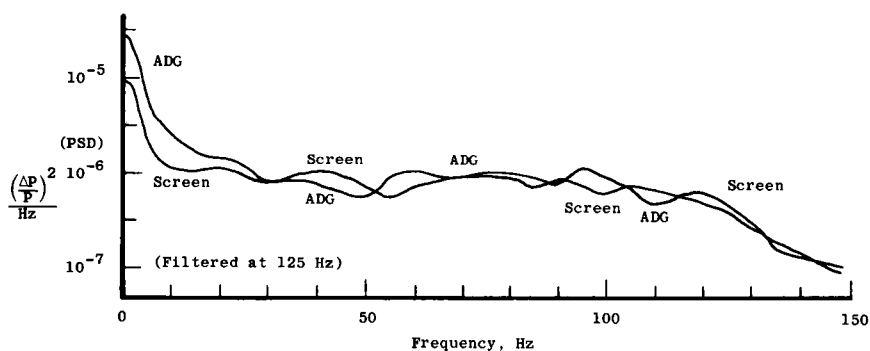
View Looking Upstream

Screen
PRMS/PF = 0.4%ADG
PRMS/PF = 1.3%

a. Engine Inlet RMS Distribution Maps for Screen and ADG System Distortion

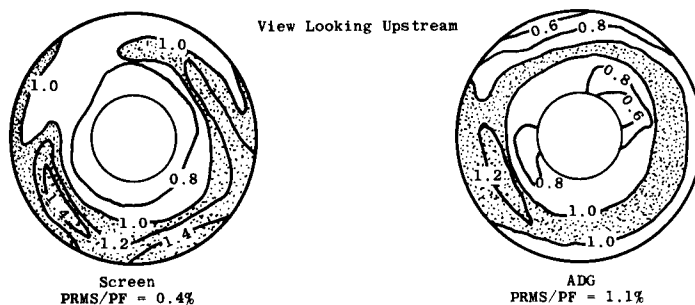


b. Distortion Indices for Screen and ADG System Distortion

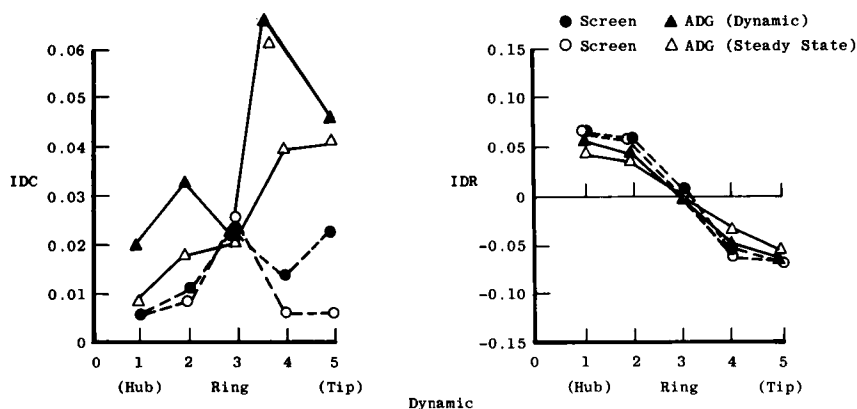


c. Power Spectral Density Characteristics for Screen and ADG System Distortion

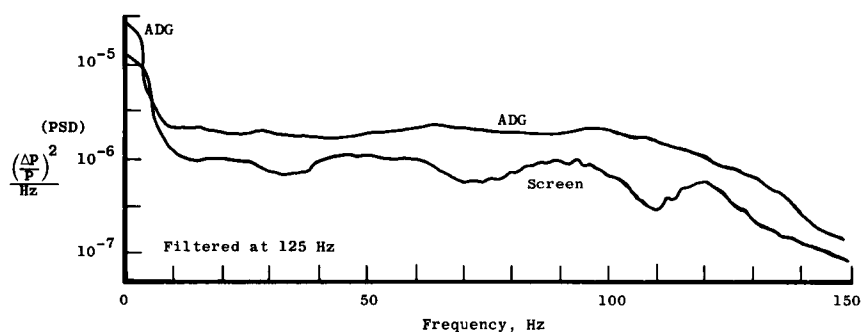
Figure 20. Dynamic distortion comparison for 50 percent hub radial pattern No. 3 (high-speed fan surge).



a. Engine Inlet RMS Distribution Maps for Screen and ADG System Distortion

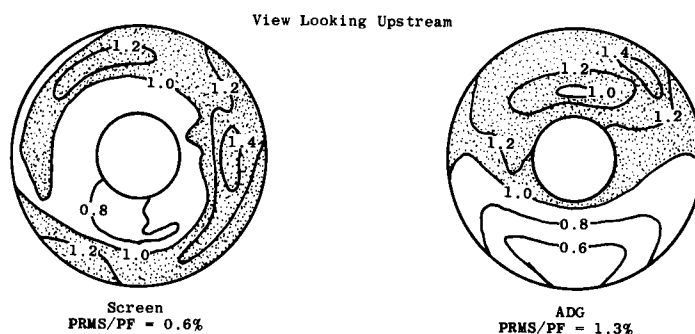


b. Distortion Indices for Screen and ADG System Distortion

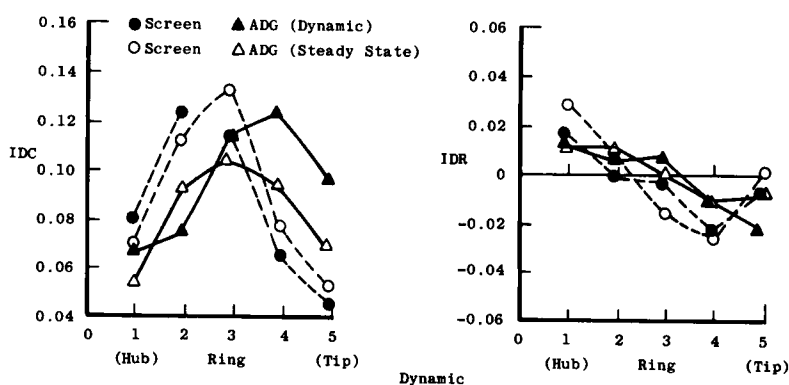


c. Power Spectral Density Characteristics for Screen and ADG System Distortion

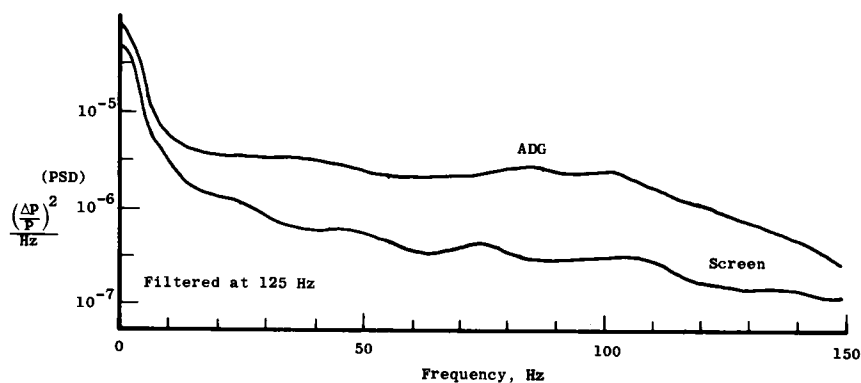
Figure 21. Dynamic distortion comparison for 50 percent hub radial pattern No. 25 (core surge).



a. Engine Inlet RMS distribution Maps for Screen and ADG System Distortion

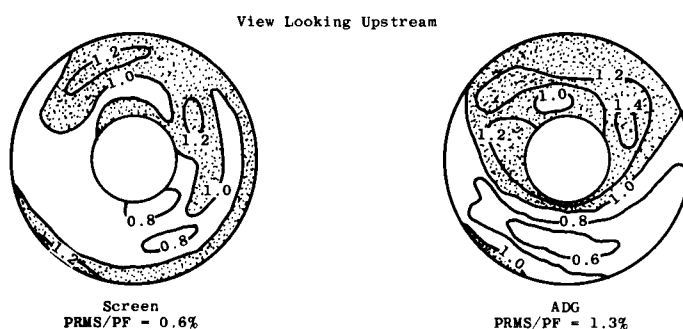


b. Distortion Indices for Screen and ADG System Distortion

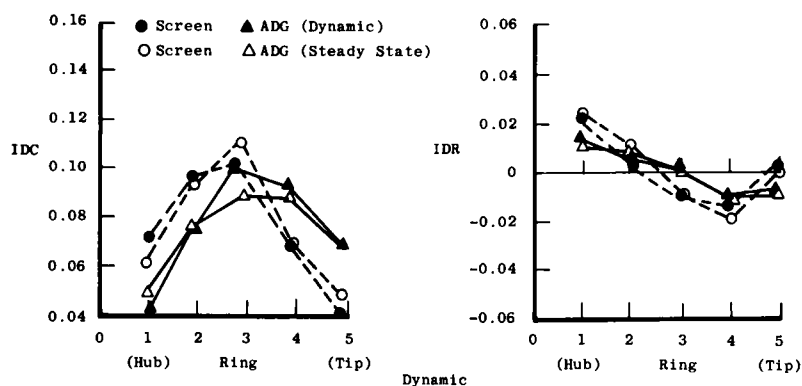


c. Power Spectral Density Characteristics for Screen and ADG System Distortion

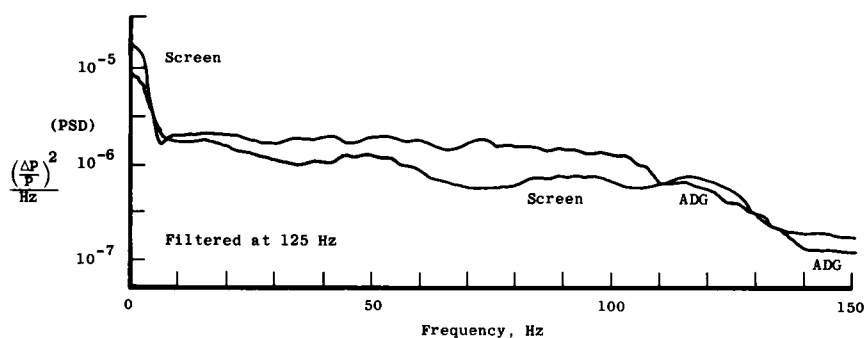
Figure 22. Dynamic distortion comparison for F101 specification pattern No. 26 (high-speed fan surge).



a. Engine Inlet RMS Distribution Maps for Screen and ADG System Distortion



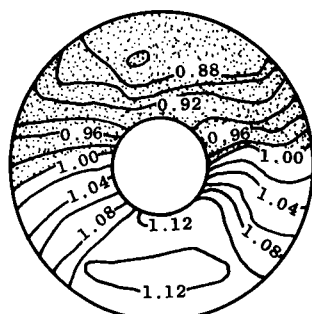
b. Distortion Indices for Screen and ADG System Distortion



c. Power Spectral Density Characteristics for Screen and ADG System Distortion

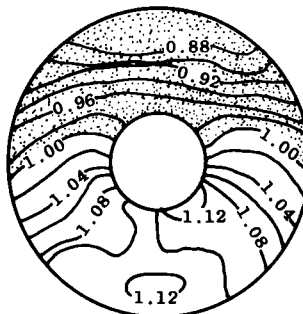
Figure 23. Dynamic distortion comparison for F101 specification pattern No. 27 (core surge).

View Looking Upstream



Screen

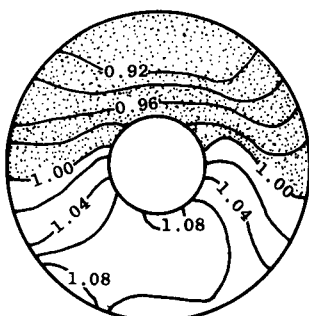
DIST1 = 26.9
IDCM = 0.128(H)
IDRM = 0.013(T)



ADG

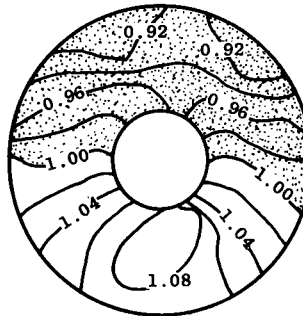
RMSE = 2.7
DIST1 = 26.9
IDCM = 0.110(T)
IDRM = 0.023(T)
IDCMD = 0.14(T)
IDRMD = 0.018(T)

a. 180-deg, 1/rev Pattern No. 1,
100 Percent Fan Speed Surge



Screen

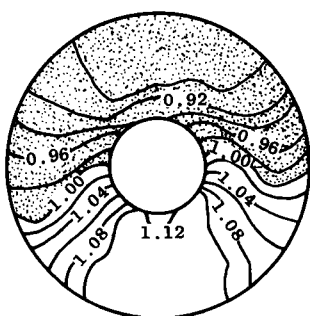
DIST1 = 16.3
IDCM = 0.074(T)
IDRM = 0.007(T)



ADG

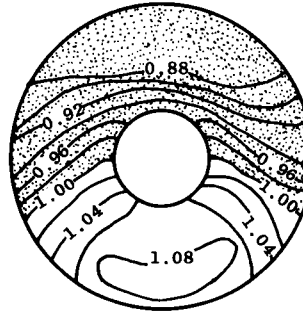
RMSE = 1.5
DIST1 = 16.8
IDCM = 0.074(T)
IDRM = 0.015(T)
IDCMD = 0.088(T)
IDRMD = 0.013(T)

b. 180-deg, 1/rev Pattern No. 2,
90 Percent Fan Speed Surge



Screen

DIST1 = 23.6
IDCM = 0.109(T)
IDRM = 0.010(T)



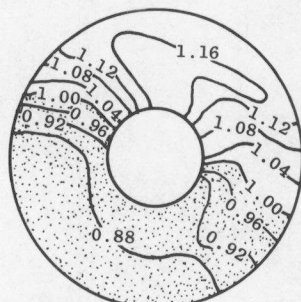
ADG

RMSE = 2.1
DIST1 = 22.8
IDCM = 0.136(H)
IDRM = 0.041(T)
IDCMD = 0.128(T)
IDRMD = 0.025(T)

c. 180-deg, 1/rev Pattern No. 23,
Core Surge

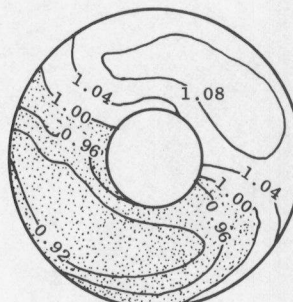
Figure 24. Steady-state distortion comparison with screen-generated patterns for other engine/rig tests.

View Looking Upstream



Screen

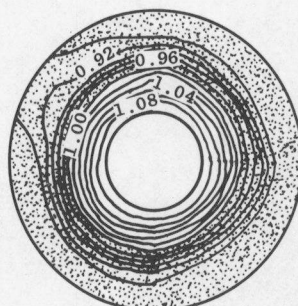
DIST1 = 32.3
IDCM = 0.138(T)
IDRM = 0.013(H)



ADG

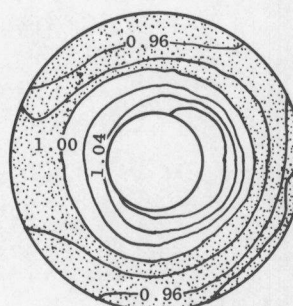
RMSE = 6.3
DIST1 = 22.1
IDCM = 0.103(T)
IDRM = 0.005(H)
IDCMD = 0.130(T)
IDRMD = 0.013(T)

d. 180-deg, 1/rev Modified Pattern No. 35,
90 Percent Fan Speed Surge



Screen

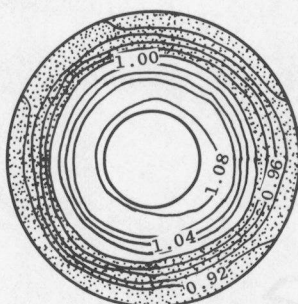
DIST1 = 23.2
IDCM = 0.020(H)
IDRM = 0.105(T)



ADG

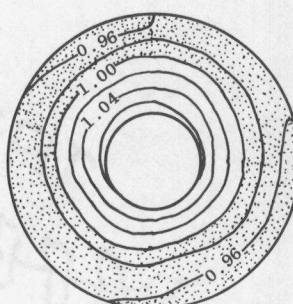
RMSE = 4.3
DIST1 = 14.3
IDCM = 0.025(T)
IDRM = 0.042(T)
IDCMD = 0.034(H)
IDRMD = 0.056(T)

e. Tip Radial Pattern No. 5,
90 Percent Fan Speed Surge



Screen

DIST1 = 16.2
IDCM = 0.009(H)
IDRM = 0.075(T)



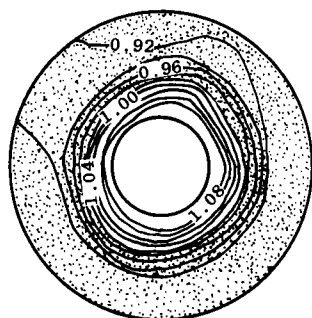
ADG

RMSE = 2.6
DIST1 = 10.9
IDCM = 0.011(T)
IDRM = 0.037(T)

f. Tip Radial Pattern No. 6,
75 Percent Fan Speed Surge

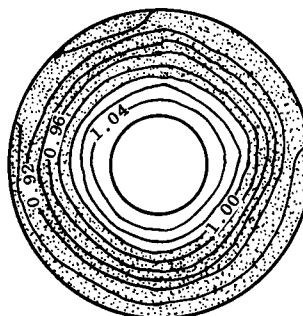
Figure 24 (Continued)

View Looking Upstream



Screen

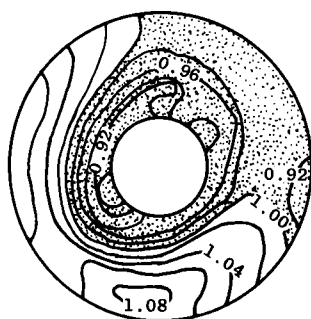
DIST1 = 17.6
IDCM = 0.008 (T)
IDRM = 0.81 (T)



ADG

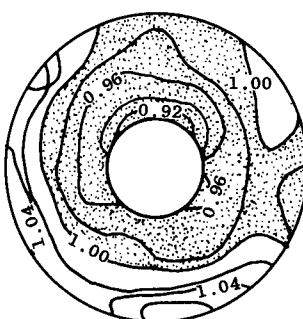
RMSE = 1.8
DIST1 = 16.2
IDCM = 0.016 (H)
IDRM = 0.081 (T)
IDCMD = 0.018 (H)
IDRMD = 0.106 (T)

g. Tip Radial Pattern No. 7,
100 Percent Fan Speed Surge



Screen

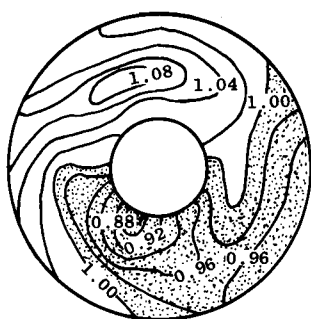
DIST1 = 20.7
IDCM = 0.065 (T)
IDRM = 0.072 (H)



ADG

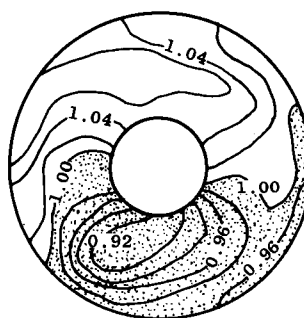
RMSE = 2.7
DIST1 = 16.3
IDCM = 0.058 (T)
IDRM = 0.050 (H)

h. Composite Pattern No. 14,
Sea-Level-Static, with Crosswind



Screen

DIST1 = 21.8
IDCM = 0.110 (H)
IDRM = 0.024 (H)



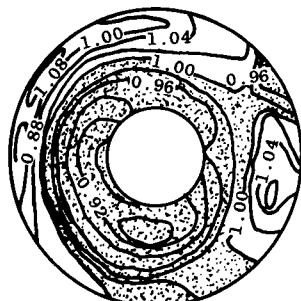
ADG

RMSE = 2.5
DIST1 = 16.9
IDCM = 0.076 (H)
IDRM = 0.019 (H)

i. Composite Pattern No. 15,
PWT Full-Scale, Sea-Level-Static

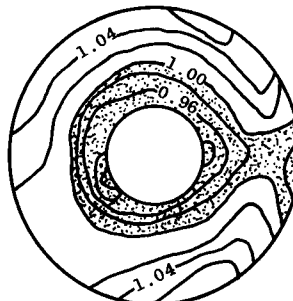
Figure 24 (Continued)

View Looking Upstream



Screen

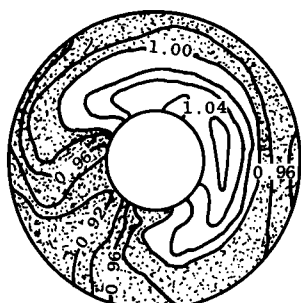
DIST1 = 22.1
IDCM = 0.071 (H)
IDRM = 0.074 (H)



ADG

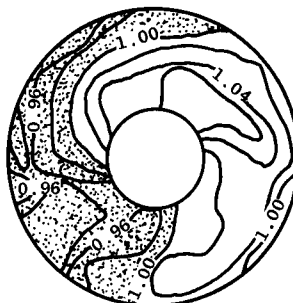
RMSE = 3.0
DIST1 = 15.6
IDCM = 0.048 (T)
IDRM = 0.059 (H)

j. Composite Pattern No. 16,
PWT Full-Scale, Sea-Level-Static



Screen

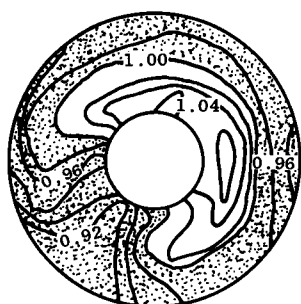
DIST1 = 16.2
IDCM = 0.104 (H)
IDRM = 0.044 (T)



ADG

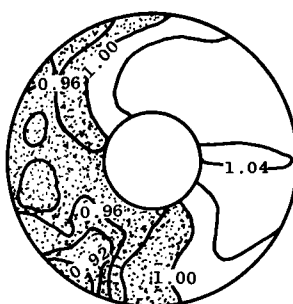
RMSE = 2.5
DIST1 = 15.9
IDCM = 0.076 (T)
IDRM = 0.015 (T)
IDCMD = 0.034 (H)
IDRMD = 0.023 (T)

k. Composite Pattern No. 30,
100 Percent Fan Speed Surge



Screen

DIST1 = 16.2
IDCM = 0.104 (H)
IDRM = 0.044 (T)



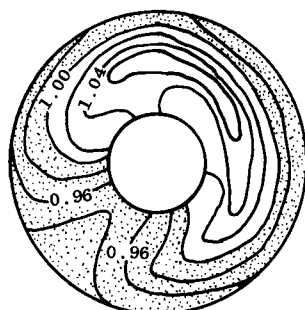
ADG

RMSE = 2.5
DIST1 = 13.3
IDCM = 0.034 (T)
IDRM = 0.010 (T)
IDCMD = 0.088 (T)
IDRMD = 0.011 (T)

l. Composite Pattern No. 31,
Core Surge

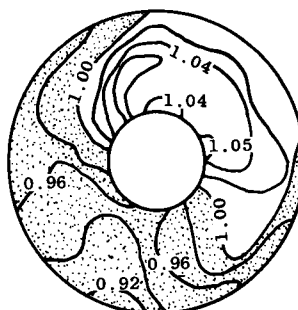
Figure 24 (Continued)

View Looking Upstream



Screen

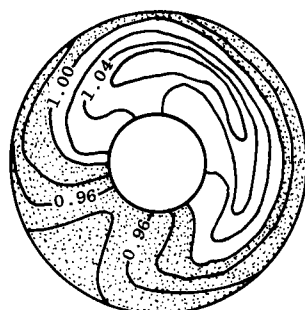
DIST1 = 13.5
IDCM = 0.084 (H)
IDRM = 0.043 (T)



ADG

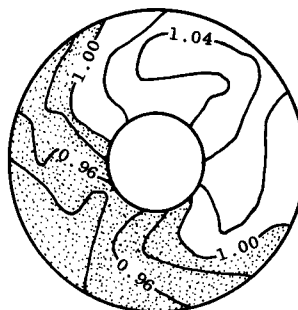
RMSE = 2.3
DIST1 = 15.3
IDCM = 0.070 (H)
IDRM = 0.024 (T)
IDCMD = 0.089 (H)
IDRMD = 0.042 (T)

m. Composite Pattern No. 32,
100 Percent Fan Speed Surge



Screen

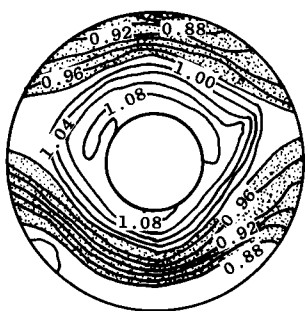
DIST1 = 13.5
IDCM = 0.084 (H)
IDRM = 0.043 (T)



ADG

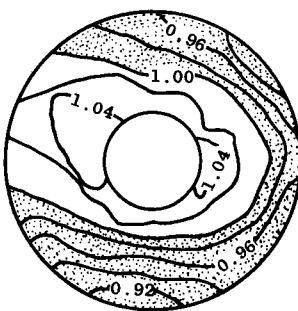
RMSE = 2.2
DIST1 = 12.7
IDCM = 0.061 (H)
IDRM = 0.016 (T)
IDCMD = 0.070 (H)
IDRMD = 0.022 (T)

n. Composite Pattern No. 33,
Core Surge



Screen

DIST1 = 24.7
IDCM = 0.084 (T)
IDRM = 0.091 (T)

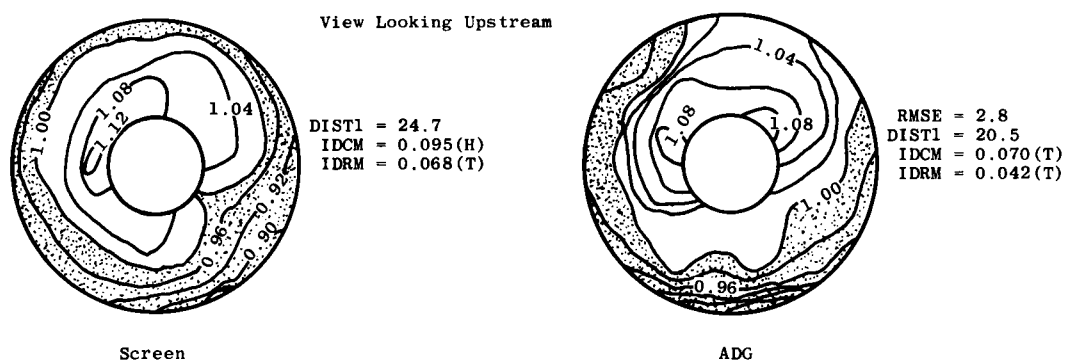


ADG

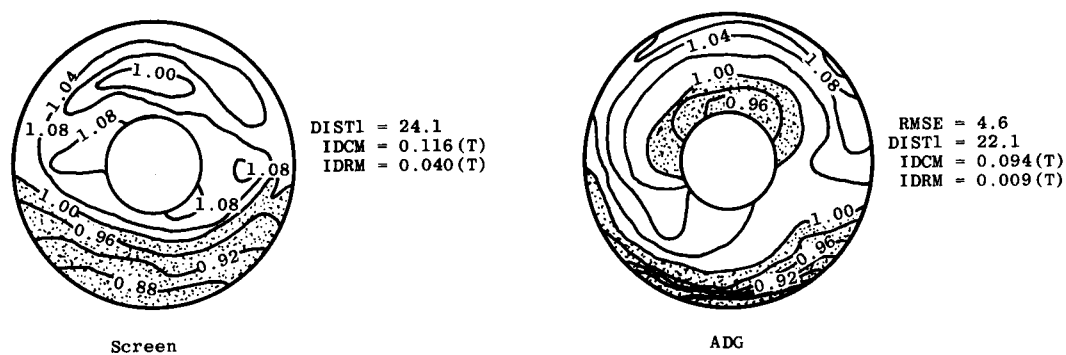
RMSE = 5.1
DIST1 = 16.8
IDCM = 0.050 (T)
IDRM = 0.042 (T)
IDCMD = 0.085 (T)
IDRMD = 0.063 (T)

o. Composite Pattern No. 11,
Simulated Supersonic

Figure 24 (Continued)



p. Composite Pattern No. 9,
Simulated Subsonic



q. Composite Pattern No. 34,
Modified Simulated Subsonic

Figure 24 (Continued)

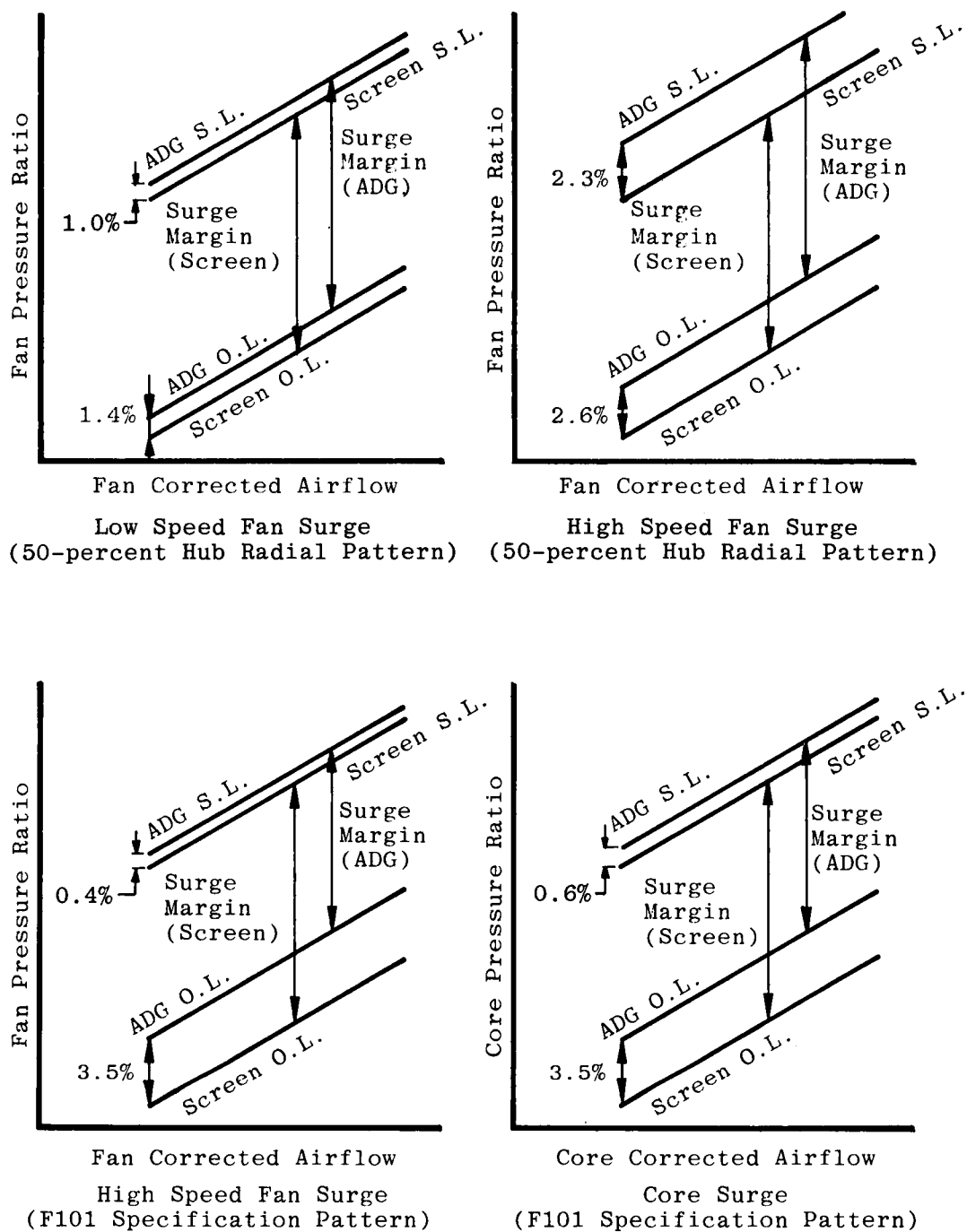


Figure 25. Comparison of surge margins for screen and ADG distortion.

$$\frac{\Delta PRS = PRS_{Clean} - PRS_{DIST1}}{PRS_{Clean}}$$

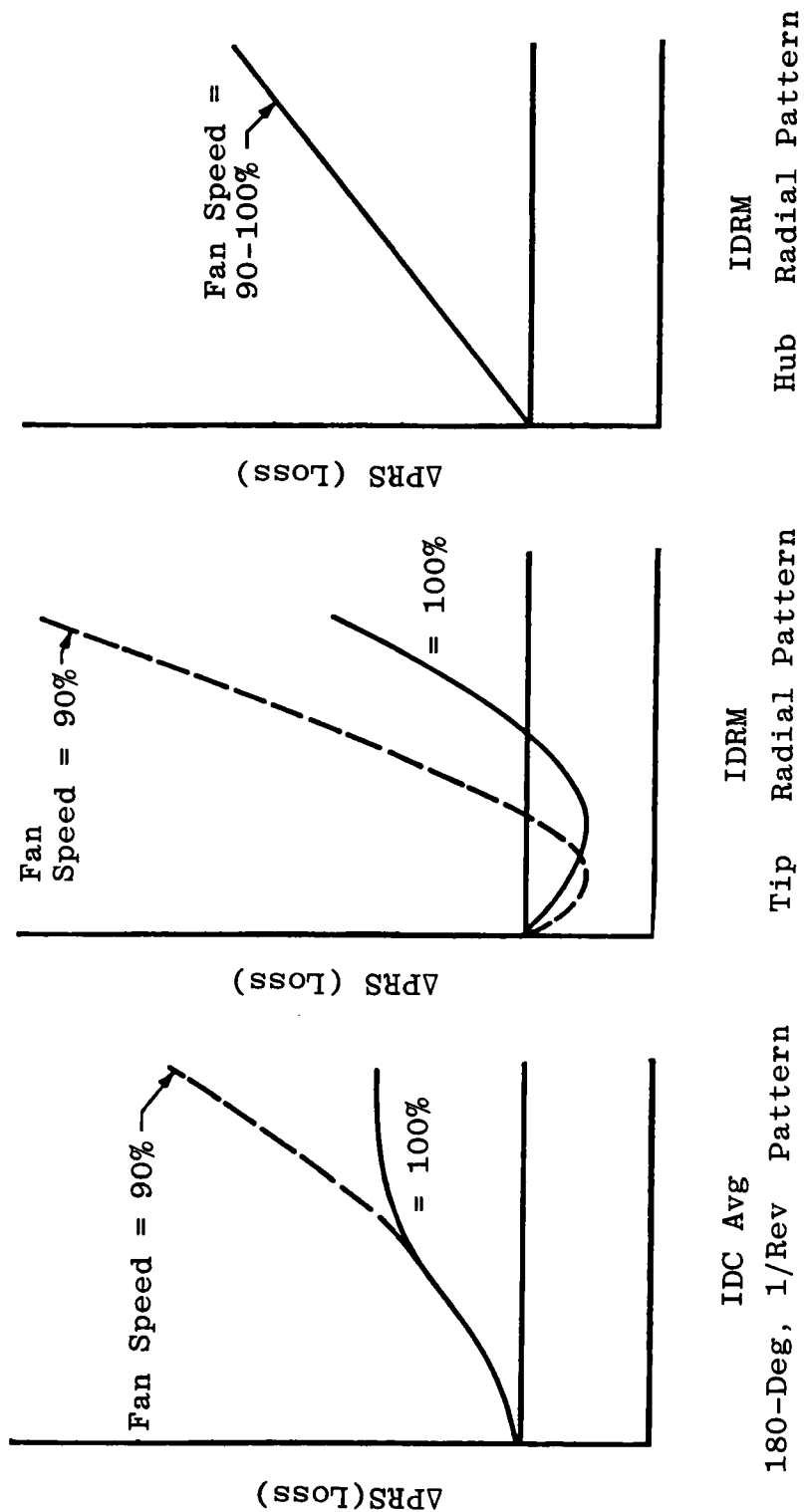


Figure 26. General Electric distortion sensitivity curves for the F101 fan.

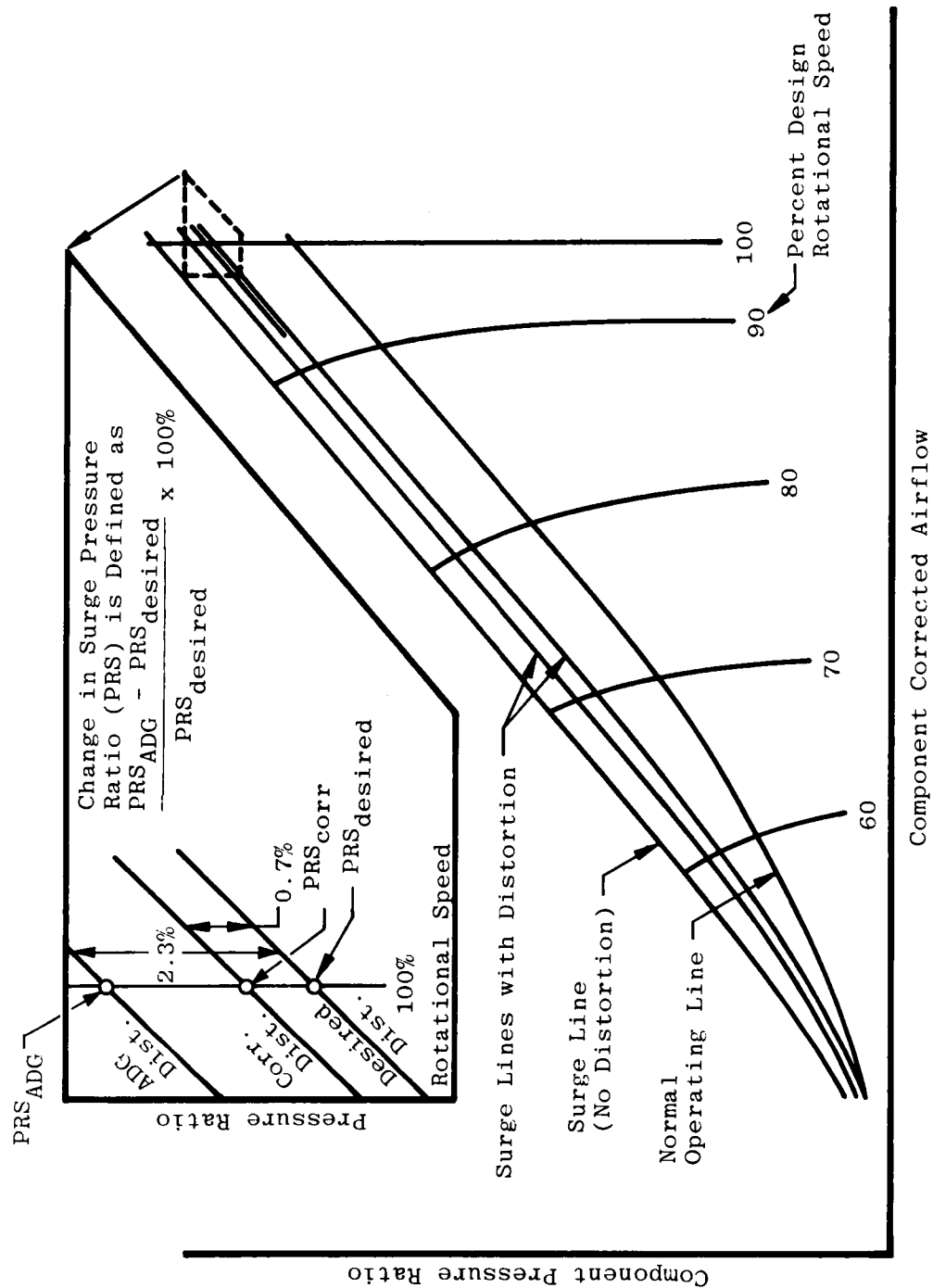
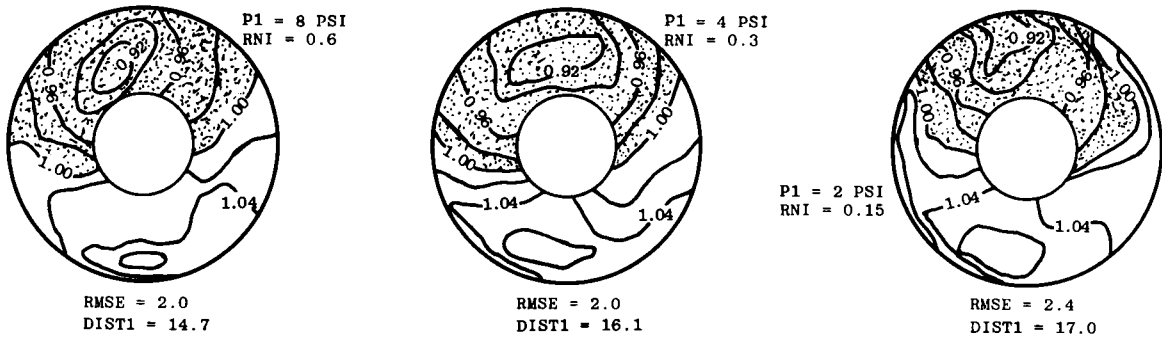
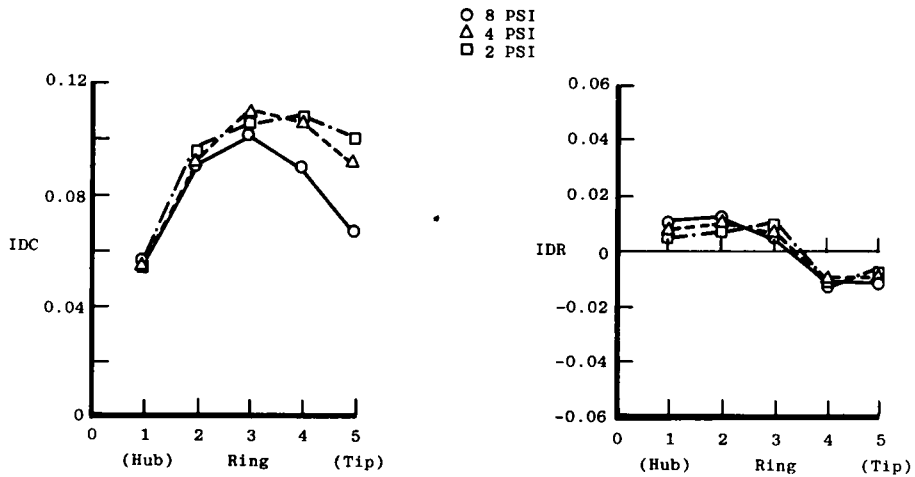


Figure 27. Typical corrected surge pressure ratio.

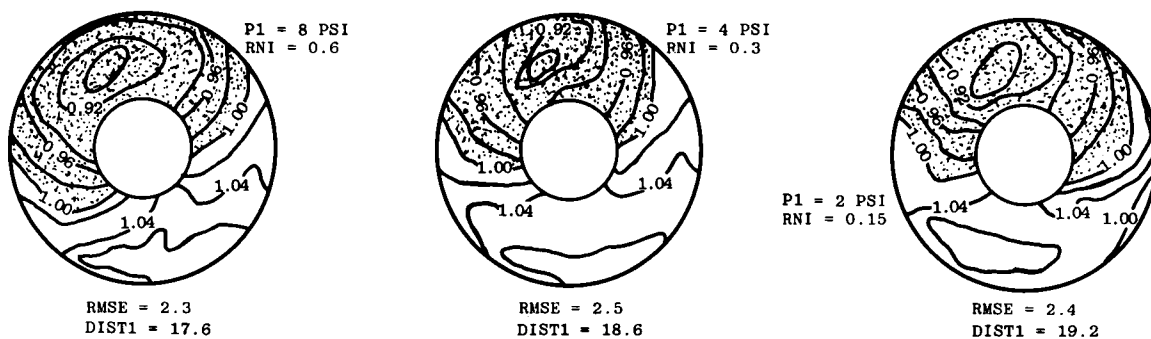


a. Engine Inlet Isobar Maps at 8, 4, and 2 psi

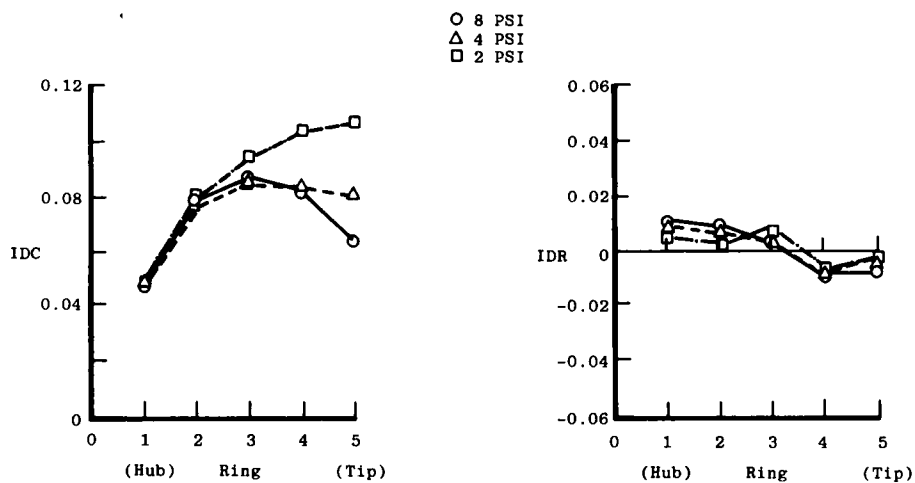


b. Distortion Indices at 8, 4, and 2 psi

Figure 28. Reynolds number effect on F101 specification pattern No. 27 at core surge (steady-state).

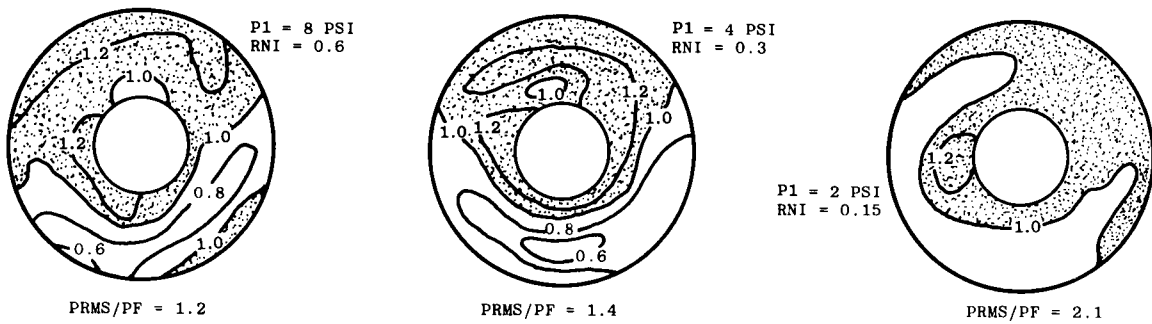


a. Engine Inlet Iso-bar Maps at 8, 4, and 2 psi

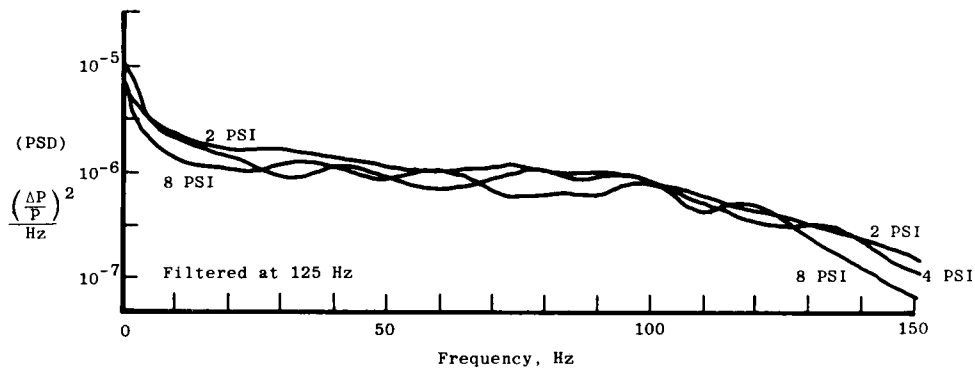


b. Distortion Indices at 8, 4, and 2 psi

Figure 29. Reynolds number effect on F101 specification pattern No. 26 at 100 percent fan speed surge (steady-state).

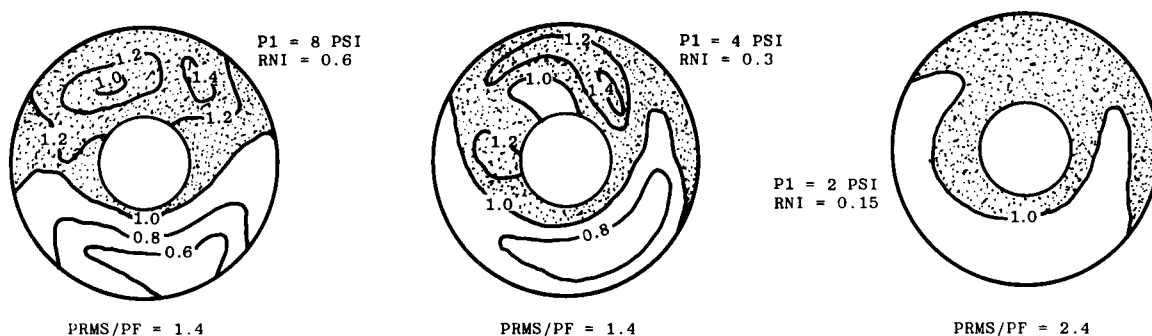


a. Engine Inlet RMS Distribution Maps at 8, 4, and 2 psi

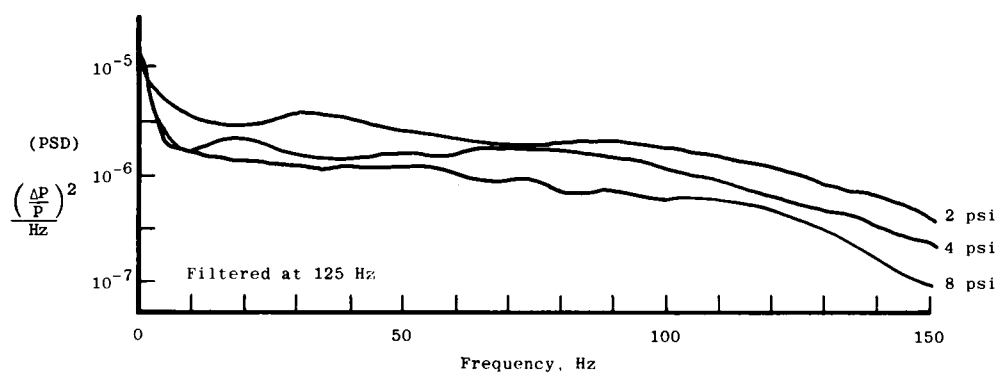


b. Power Spectral Density Characteristics at 8, 4, and 2 psi

Figure 30. Reynolds number effect on F101 specification pattern No. 27 at core surge (dynamic).

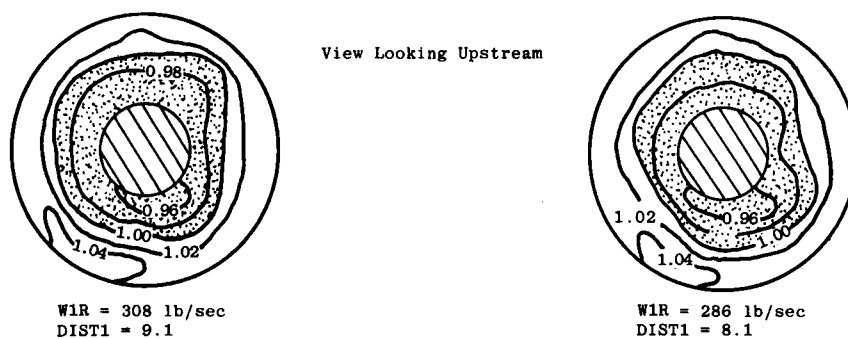


a. Engine Inlet RMS Distribution Maps at 8, 4, and 2 psi

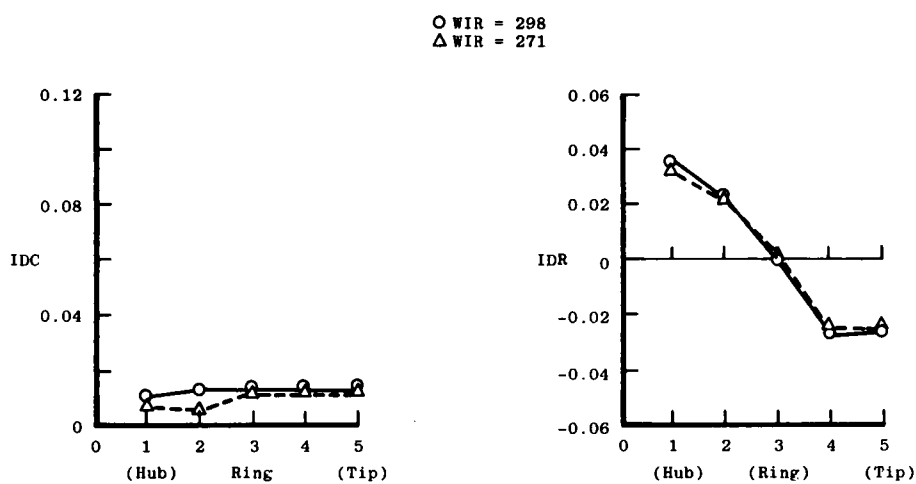


b. Power Spectral Density Characteristics at 8, 4, and 2 psi

Figure 31. Reynolds number effect on F101 specification pattern No. 26 at 100 percent fan surge (dynamic).



a. Engine Inlet Isobar Maps
During Airflow Change

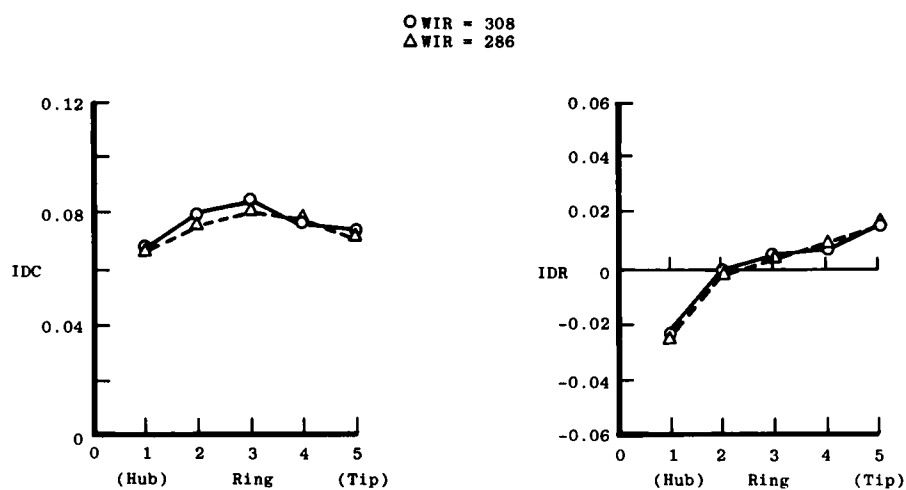


b. Distortion Indices During
Airflow Change

Figure 32. Stability during airflow change for
50 percent hub radial pattern.



a. Engine Inlet Isobar Maps
During Airflow Change



b. Distortion Indices During
Airflow Change

Figure 33. Stability during airflow changes for 180-deg, 1/rev pattern.

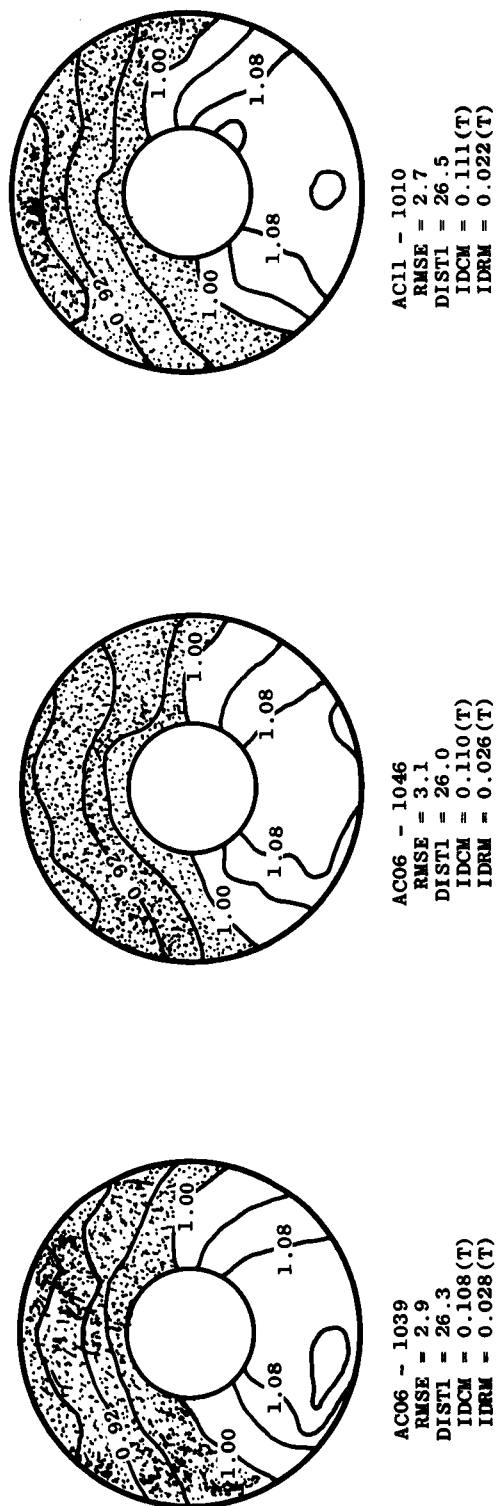
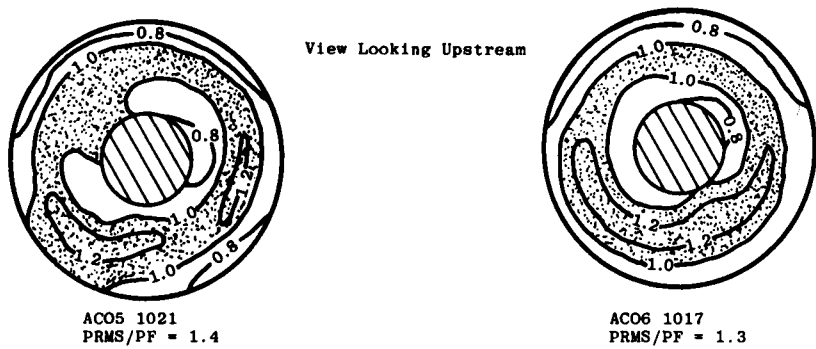
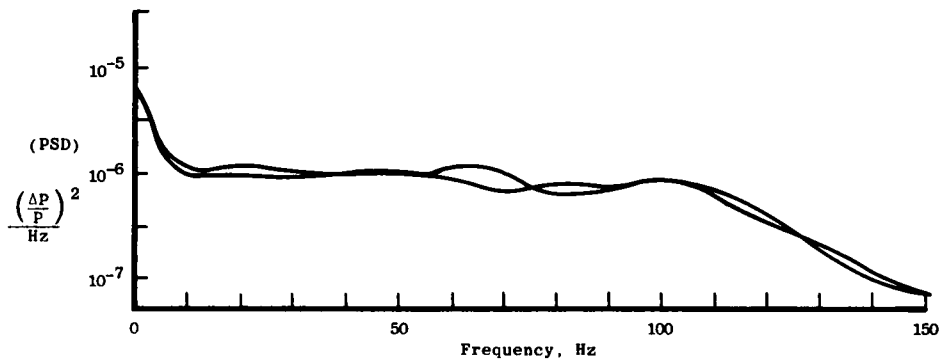


Figure 34. Pattern repeatability (steady-state).



a. Engine Inlet RMS Distribution Maps



b. Power Spectral Density Characteristics

Figure 35. Pattern repeatability (dynamic).

APPENDIX B

TABLES

Table 1. Test Matrix

Pattern Number	Description	W1R (lbm/sec)	P1 _{avg} (psia)
1	Screen No. 106; 180-deg, 1/rev pattern at fan surge	350	8
2	Screen No. 106; 180-deg, 1/rev pattern at fan surge	300	8
3	Screen No. 141; 50 percent hub radial pattern at fan surge	350	8
4	Screen No. 141; 50 percent hub radial pattern at fan surge	300	8
5	Screen No. 123C; 50 percent tip radial pattern at fan surge	300	8
6	Screen No. 123C; 50 percent tip radial pattern at fan surge	230	8
7	Screen No. 121; 50 percent tip radial pattern at fan surge	350	8
9	Screen No. 351.1; simulated supersonic pattern	350	8
11	Screen No. 353CD; simulated supersonic pattern	300	8
12	Screen No. 352.4CD; simulated supersonic pattern	225	8
13	Screen No. 355.1; simulated supersonic pattern	230	8
14	Flight test, sea-level-static with crosswind pattern	350	8
15	PWT full-scale, sea-level-static (P/P 237509)	350	8
16	PWT full-scale (P/P 220801)	350	8
23	Screen No. 106; 180-deg, 1/rev pattern at core surge	350	8
24	Screen No. 106; 180-deg, 1/rev pattern at core surge	300	8
25	Screen No. 141; 50 percent hub radial pattern at core surge	350	8

Table 1 (Continued)

Pattern Number	Description	W1R (lbm/sec)	P1 _{avg} (psia)
26	Screen No. 354.7M; simulated sea-level-static pattern at fan surge	350	8,4,2
27	Screen No. 354.7M; simulated sea-level-static pattern at core surge	350	8,4,2
28	Screen No. 303.4; modified 1/rev pattern	300	8
30	Flight test pattern at fan surge	350	8
31	Flight test pattern at core surge	350	8
32	Flight test pattern at fan surge	350	8
33	Flight test pattern at core surge	350	8,4
34	Screen No. 356.1; simulated subsonic pattern	350	8,4
35	Screen No. 303.4; modified 1/rev pattern at fan surge	300	8

Table 2. Calculated Parameter Uncertainties for Steady-State Data

Parameter Designation	Precision Index		Bias		Uncertainty		Range (%)
	% Reading	Meas. Units	% Reading	Meas. Units	% Reading	Meas. Units	
DIST1	--	0.3	--	0.3	--	0.9	5 to 20
IDC	--	0.3	--	0.3	--	0.9	5 to 20
IDR	--	0.3	--	0.3	--	0.9	5 to 20

Table 3. Calculated Parameter Uncertainties for Time-Averaged Transient Data

Parameter Designation	Precision Index		Bias		Uncertainty		Range
	% Reading	Meas. Units	% Reading	Meas. Units	% Reading	Meas. Units	
WSA	1.1	--	2.2	--	5.3	--	1 to 6 lb/sec
WY1P	1.36	--	0.71	--	3.4	--	2 to 8 psia
	0.34	--	0.31	--	1.0	--	8 to 30 psia
W1R	1.82	--	0.96	--	4.6	--	2 to 8 psia
	0.48	--	0.44	--	1.4	--	8 to 30 psia
PRS	1.91	--	0.93	--	4.7	--	2 to 8 psia
	0.48	--	0.24	--	1.2	--	8 to 30 psia
DIST1	--	1.0	--	0.4	--	2.4	5 to 20 %
IDC	--	1.0	--	0.4	--	2.4	5 to 20 %
IDR	--	1.0	--	0.4	--	2.4	5 to 20 %

Table 4. Pattern Matches During Baseline Testing

Pattern Number	Screen Number	Fan Speed (%)	RMSE (%)	DIST1 (%) Screen ADG	Figure Number
<u>180-deg, 1/rev</u>					
1	106	100	2.5	26.9	26.2 12
23	106	95	2.5	23.6	23.4 13
2	106	90	2.5	16.3	17.9 11
<u>50% Hub Radial</u>					
3	141	100	2.4	16.8	15.1 15,20
25	141	94	2.0	14.0	13.1 16,21
4	141	90	1.1	9.8	10.2 14,19
<u>F101 Spec.</u>					
26	354.7M	100	2.3	23.4	17.5 17,22
27	354.7M	93	1.7	20.0	15.5 18,23

Table 5. Pattern Matches (Other Than Baseline)

Pattern Number	Screen Number	Fan Speed (%)	RMSE (%)	DIST1 (%)		Figure Number
<u>180-deg, 1/rev</u>						
	106	100	2.7	26.9	26.9	24a
1	106	100	2.7	26.9	26.9	24a
23	106	94	3.1	23.6	22.8	24c
2	106	90	1.5	16.3	16.8	24b
35	303.4	90	6.3	32.3	22.1	24d
<u>50% Tip Radial</u>						
7	121	100	1.8	17.6	16.2	24g
5	123C	90	4.3	23.2	14.3	24e
6	123C	75	2.6	16.2	10.9	24f
<u>F101 Spec.</u>						
11	353CD	90	5.1	24.7	16.8	24e
9	353.1	100	2.8	24.7	20.5	24p
34	356.1	100	4.6	24.1	22.1	24q

Table 5 (Continued)

Pattern Number	Screen Number	Fan Speed (%)	RMSE (%)	DIST1 (%) Screen	ADG	Figure Number
<u>B-1 Flt. Test</u>						
14	SLS - C/W	100	2.7	20.7	16.3	24h
<u>Inlet Model</u>						
15	PWT - SLS	100	2.5	21.8	16.9	24i
16	PWT - SLS	100	3.0	22.1	15.6	24j
<u>Special (Composite Patterns)</u>						
30	GE No. 4	97	2.5	16.2	15.9	24k
31	GE No. 4	93	2.5	16.2	13.3	24l
32	GE No. 2	100	2.3	13.5	15.3	24m
33	GE No. 2	95	2.2	13.5	12.7	24n

Table 6. Engine Stability Comparison for Baseline Tests

Pattern Number	Screen Number	Airflow at Surge (ADG) (lb/sec)	Type Surge	RMSE (%)	Surge Pressure Ratio ¹ Comparison (%)
<u>180-deg, 1/rev</u>					
1	106	348	Fan	2.5	+1.0
23	106	330	Core	2.5	0
<u>50% Hub Radial</u>					
3	141	342	Fan	2.4	+2.3
4	141	286	Fan	1.1	+1.0
25	141	320	Core	2.0	-1.4
<u>F101 Spec.</u>					
26	354.7M	343	Fan	2.3	+0.4
27	354.7M	320	Core	1.7	+0.6

$$^1 (PRS_{ADG} - PRS_{SCR}) \times 100 / PRS_{SCR} \cdot$$

Table 7. Engine Stability Comparison (Other Than Baseline)

Pattern Number	Screen Number	Airflow at Surge (ADG) (lb/sec)	Type Surge	RMSE (%)	Surge Pressure Ratio ¹ Comparison (%)
<u>180-deg, 1/rev</u>					
1	106	345	Fan	2.7	-1.6
2	106	271	Fan	1.5	+2.6
23	106	314	Core	2.1	-0.9
35	303.4	276	Fan	6.3	+6.3
<u>50% Tip Radial</u>					
7	121	331	Fan	1.8	-2.3
5	123C	277	Fan	4.3	+15.9
<u>F101 Spec.</u>					
11	353CD	276	Fan	5.1	+13.8

$$^1 (PRS_{ADG} - PRS_{SCR}) \times 100 / PRS_{SCR} \cdot$$

Table 8. Surge Pressure Ratio Comparison After
Correction to Desired Distortion Level¹

Pattern Number	Screen Number	Fan Speed (%)	Surge Pressure Ratio Comparison, % ¹		
			Measured	Corrected ² (Steady-State)	Corrected ² (Dynamic)
3	141	100	2.3	0.7	0.7
4	141	90	1.0	0.2	0.2
1	106	100	-1.6	-1.9	-1.8
2	106	90	2.6	2.6	3.9
7	121	100	-2.3	-2.3	2.6
5	123C	90	15.9	-2.0	2.0
35	303.4	90	6.3	-3.2	1.8

¹ $(PRS_{ADG} - PRS_{SCR}) \times 100 / PRS_{SCR}$.

² General Electric distortion sensitivity curves used for corrections.

VITA

Jerry Dean Hubble was born in Marion, Virginia, on February 20, 1954. He attended elementary schools at Nebo and Rich Valley in Smyth County, Virginia, and was graduated from Rich Valley High School in June, 1972. That summer he entered Virginia Polytechnic Institute and State University, and in June, 1976, he received a Bachelor of Science degree in Aerospace and Ocean Engineering.

In the summer of 1976 he accepted a research assistantship at Virginia Polytechnic Institute and State University, and began study toward a Master of Science degree. He accepted a position with ARO, Inc., in December, 1976, and continued study, on a part-time basis, at The University of Tennessee Space Institute. In March, 1979, he was awarded the Master of Science degree in Mechanical Engineering.

Mr. Hubble is married to the former Anne Pratt of Rich Valley, Virginia.