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Gas Turbine Engine Inlet Flow Distortion Guidelines

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1. SCOPE:

The turbine-engine inlet flow distortion methodology addressed in this document applies only to the effects of inlet total-pressure distortion. Practices employed to quantify these effects are developing and therefore, periodic updates are anticipated. The effects of other forms of distortion on flow stability and performance and of any distortion on aeroelastic stability are not addressed.

The guidelines can be used as necessary to create a development method to minimize the risk of inlet/engine compatibility problems. The degree to which guidelines for descriptor use, assessment techniques, and testing outlined in this document are applied to a specific program should be consistent with the expected severity of the compatibility problem.

1.1 Purpose:

This Aerospace Recommended Practice (ARP) provides guidelines by which gas turbine engine aerodynamic stability and performance, as affected by the quality of the airflow delivered to the engine, can be evaluated consistently. The following subjects are addressed:

1.1.1 Distortion Descriptors: Distortion descriptors are presented that permit the representation and evaluation of inlet total-pressure distortion effects on propulsion system stability and performance.

1.1.2 Stability Assessment: Guidelines are presented for developing an evaluation method that relates the distortion descriptor levels to engine stability in a form suitable for use in computer simulations.

1.1.3 Testing: Guidelines are provided for testing, instrumentation, data acquisition, and data processing.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP246	Orientation of Engine Axis, Coordinate and Numbering Systems for Aircraft Gas Turbine Engines
AS681	Gas Turbine Engine Steady-State and Transient Performance Presentation for Digital Computer Programs
ARP755	Aircraft Propulsion System Performance Station Designation and Nomenclature
ARP1210	Gas Turbine Engine Interface Test Data Reduction Computer Programs
ARP1257	Gas Turbine Engine Transient Performance Presentation for Digital Computer Programs (Cancelled)

2.2 Symbols:

C	Offset term (Equation A12)
C(τ)	Covariance of time varying pressures
K	Distortion sensitivity (Equation A12)
L	Characteristic length (cowl lip to compressor face)
MPR	Multiple-per-revolution element
N	Number of rings
P	Total pressure
$\overline{P}$	Time-averaged total pressure
PAV	Ring average total pressure
PAVLOW	Average total pressure of low total-pressure region for a ring (Equations A3 and A7)
PFAV	Face average total pressure (Paragraph A.1.2)
PR	Pressure ratio of given compression components
PRDS	Surge pressure ratio with distortion
PR0	Operating pressure ratio
PR1	Undistorted surge pressure ratio
P(θ)	Total pressure at any angle θ for a given ring
Q	Number of low-pressure regions
R	Radius
RMS	Root mean square
SM	Surge margin
T	Total temperature
f	Frequency

2.2 (Continued):

$\Delta PC/P$	Circumferential distortion intensity element (Equations A2 and A6)
$\Delta PR/P$	Radial distortion intensity element (Equation A10)
$\Delta PRMS$	Root mean square of time varying total-pressure fluctuations
ΔPRS	Surge pressure ratio loss (Equation A12)
ΔSM	Surge margin loss (Equation A13)
θ	Circumferential location in degrees
θ^+	Extent of high-total-pressure region
θ^-	Extent of low-total-pressure region
τ	Time increment
ϕ (f)	Power spectral density of time-varying pressure

Subscripts

i	Ring number
j	Rake number
k	Low-pressure region number
MAX	Maximum
MIN	Minimum

3. PROVISIONS:

Guidelines are provided to:

3.1 Identify the inlet/engine Aerodynamic Interface Plane (AIP) (Section 7).

3.2 Express inlet flow distortion data in terms of numerical distortion descriptor elements (Section 4 and the Appendix).

3.3 Quantify engine compressor surge margins (Section 5).

3.4 Provide an empirical correlation technique for translating distortion descriptors into parameters suitable for stability and performance assessments (See Appendix).

3.5 Provide an inlet distortion procedure, useful for both engine and inlet development, to identify potentially critical stability conditions (Section 4).

3.6 Conduct assessments to quantify the effects of inlet distortion on engine stability and performance (Section 5).

3.7 Recommend inlet and engine tests to evaluate propulsion system stability and to develop engine stability and performance assessments.

3.8 Provide the aerodynamic stability and performance information for use by ARP1257 and AS681C.

4. DISTORTION DESCRIPTOR FORMAT AND USAGE:

The AIP pressure-probe data are used to describe inlet distortion directly in terms of the probe readings (pattern) and numerically in terms of a distortion descriptor that is related to the severity of the distortion. The distortion descriptor provides a means of identifying critical inlet flow distortions and of communicating during propulsion system development. A universal distortion descriptor is beyond the state of the art; however, distortion-descriptor elements have been identified for use in structuring a distortion descriptor for a particular engine. These elements should be used to define each distortion descriptor system and its associated computation procedure.

4.1 Distortion-Descriptor Elements:

The distortion-descriptor elements are used to describe the distortion at the AIP. The fundamental element is the set of pressure-probe readings that are used to describe the pressure distribution at the AIP. The pressure probes are usually arranged in rake and probe arrays, as described in Section 7 (Figure 2). Circumferential and radial distortion elements (obtained using the pressure-probe readings) are described on a ring-by-ring basis, as described below and in detail in the Appendix.

4.1.1 Circumferential Distortion Elements: Circumferential distortion is described in terms of intensity, extent, and multiple-per-revolution elements.

4.1.1.1 Intensity: The circumferential distortion intensity element ($\Delta PC/P$) describes the magnitude of the pressure defect for each ring.

4.1.1.2 Extent: The circumferential distortion extent element for each ring (θ^-) is the angular region, in degrees, in which the pressure is below ring average pressure.

4.1.1.3 Multiple-per-Revolution: The circumferential distortion multiple-per-revolution element (MPR) describes the number of low-pressure regions for each ring.

4.1.2 Radial Distortion Element: The radial distortion intensity element ($\Delta PR/P$) describes the difference between the ring average pressure and the face average pressure for each ring. Both positive and negative values of radial intensity are considered. Positive values reflect an average ring pressure that is below the face average pressure.

4.2 Inlet Distortion Descriptors:

By a combination of the distortion-descriptor elements described above and the stability and performance assessment techniques described in Section 5, the developer will define a set of inlet distortion descriptors for use in describing inlet distortion levels at the AIP. These descriptors may be used for inlet distortion screening to evaluate inlet/engine compatibility prior to any inlet/engine testing. Inlet distortion screening is accomplished by converting the probe readings at the AIP into numerical distortion descriptors, which are then compared to allowable levels of distortion based on a stability and performance assessment of a specific engine model.

5. STABILITY AND PERFORMANCE ASSESSMENT:

Quantitative evaluations of compressor stability and engine performance may be necessary to provide technical visibility relative to target levels. Assessments should be carried out regularly, in increasing detail, during development and periodically throughout the propulsion system life cycle.

5.1 Surge Margin (SM):

The ARP1420 definition for surge margin is

$$SM = ((PR1 - PR0)/PR0) \times 100 \qquad \text{(Eq. 1)}$$

with nomenclature defined as in Figure 1. As shown, surge margin is defined at the operating airflow and normalized by the operating pressure ratio. Particular engine configurations may require alternate definitions of surge margin which are more appropriate. In such cases, the user should specify his definition of surge margin, surge margin loss, and assessment procedures.

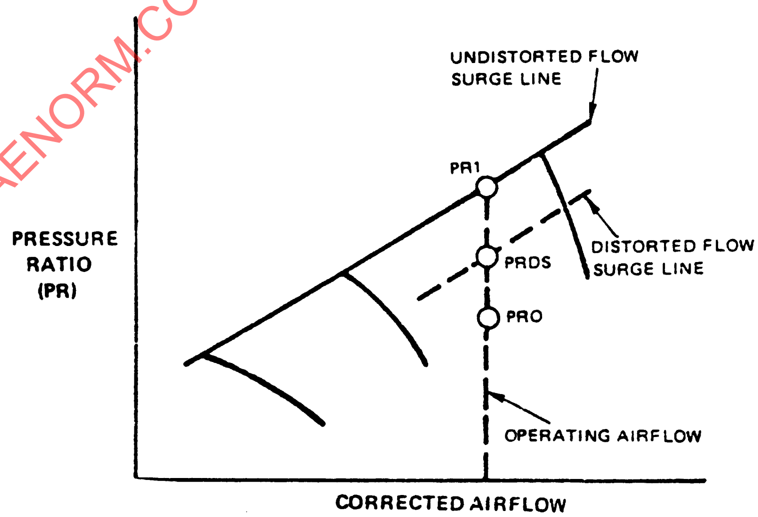

FIGURE 1 - Surge Margin Definition

5.2 Surge Pressure Ratio Loss (ΔPRS):

The ARP1420 definition for loss in surge pressure ratio (ΔPRS) is

$$\Delta PRS = ((PR1 - PRDS) / PR1) \times 100 \quad \text{(Eq. 2)}$$

with nomenclature defined in Figure 1. Surge pressure ratio loss is defined at constant corrected airflow.

5.3 Stability Assessment:

A stability assessment provides quantitative estimates of the effects of inlet distortion and other destabilizing influences on compressor surge margin. The assessment should be so performed as to reveal the surge margin utilization by accounting for factors that lower component surge lines and raise their operating lines. The assessment, performed at constant engine-corrected airflow (the matched inlet-engine corrected airflow at the steady-state operating point corresponding to the propulsion system operating condition being investigated), requires that component surge lines and the distortion sensitivities be evaluated over the entire corrected-airflow operating range for each compressor.

Factors to be considered include time-variant inlet distortion, in-phase pressure oscillations, component interactions, deterioration, component variation due to manufacturing tolerance, control tolerances, variable-geometry position, power-lever transients, operating-point shift with distortion, Reynolds number effect, compressor bleed, and horsepower extraction.

The effect of each factor is expressed as a change in surge margin. The loss in surge margin due to distortion is computed from the distortion-descriptor elements using the guidelines of A.2 of the Appendix. Individual effects are combined to determine the net surge margin: some effects are cumulative and should be added algebraically, whereas other effects should be added statistically. The method and rationale for combining individual effects should be delineated and supported by test experience.

Distortion transfer coefficients are used to translate inlet distortion effects to the downstream components. Assessments are made for each compression system component.

5.4 Performance Assessment:

A performance assessment provides quantitative estimates of the effects of inlet distortion on engine thrust, airflow, and fuel consumption. It is desirable to correlate the performance changes with the distortion descriptor elements defined in the Appendix. The assessment is performed at specified propulsion system operating conditions and the corresponding matched inlet-engine AIP conditions (airflow, inlet distortion, and inlet ram recovery).

Current practice is to use steady-state descriptor elements to correlate changes in compression system speed, flow, and efficiency relationships. Performance calculations are then used to estimate the overall effects of distortion on engine thrust, airflow, and fuel consumption. Test data indicate that compressor speed-flow relationships and efficiency can be affected by the unsteady elements of time-variant distortion. If these time-variant distortion effects are sufficiently large, they should be included in the performance assessment.

6 TESTING:

Testing during propulsion system development may be required to develop and verify stability and performance assessments. The validity of the assessments depends on the quality of the data bank generated during the testing effort.

6.1 Test Planning:

A time-phased test program which defines test techniques, instrumentation, data management, test equipment and procedures, and the analysis and communication of test results should be agreed upon by all involved parties.

6.2 Testing Scope:

Tests which may be required prior to production will depend on the propulsion system under development. The types of test and test objectives are as follows:

6.2.1 Inlet and Aircraft Component Tests: These tests include scale-model inlet/forebody tests, control bench tests, and full-scale or large-model tests with inlet control. The objective of these tests is to provide data for inlet development, distortion level and pattern definition, off-schedule geometry and bleed effects, inlet stable flow range, and definition of control system/inlet destabilizing effects.

6.2.2 Engine and Engine Component Tests: These consist of compressor, diffuser, control, burner, augmentor, fuel system, and engine tests with and without inlet pressure distortion. The objective of the tests is to provide data for distortion-descriptor development, control and sensor development, scheduled and off-schedule geometry and bleed effects, Reynolds number effects, component interactions, engine performance, and stability evaluation. Surge data should be obtained whenever practical.

6.2.3 Propulsion System Tests: These tests consist of static, simulated altitude, and flight tests. The objectives of the tests are to evaluate propulsion system stability, system operational characteristics, failure modes, and control interactions throughout the flight and maneuver envelopes.

6.3 Stability and Performance Tests:

Tests should be conducted at environmental conditions representative of projected mission-related flight conditions. Inlet and engine operating conditions must be defined and should include the following:

6.3.1 Inlet: Inlet configuration details, mass flow ratio, corrected airflow, Reynolds number, Mach number, aircraft angles of attack and yaw, and bleed flows.

6.3.2 Engine: Engine configuration details, operating corrected speeds, corrected airflow, bleed flows, power extraction requirements, control function (steady-state or transient), operating mode (after-burning, non-afterburning, etc.), compressor face total pressure and total temperature, and compressor inlet distortion pattern (probe values).

Engine tests provide data for assessment verification and documentation. Compressor surge-line and surge-margin utilization data together with compressor speed, flow, and efficiency changes are obtained from tests on representative components.

During stability testing, engine operation in the region above the maximum predicted operating line and below the predicted surge pressure ratio should be accomplished whenever practical. Surge data for the stability assessment may be obtained by use of compressor loading techniques that account for engine control logic and mechanical limitations. Documentation should include operating-line excursions caused by the primary stability degrading factors such as inlet distortion and control requirements. The compressor surge margin utilization estimated for engine aging factors such as deterioration should be verified on the basis of life-cycle and/or service engine tests of production engines.

Engine performance testing should establish thrust, fuel flow and airflow characteristics with the inlet total-pressure recovery and distortion applied.

7. INTERFACE INSTRUMENTATION AND DATA MANAGEMENT:

Guidelines are provided for data scaling, total-pressure instrumentation, data acquisition, and data processing.

7.1 Data-Scaling:

Inlet models should be sized to maintain Reynolds number greater than values below which significant changes in inlet recovery and distortion may occur.

Time-variant-distortion scaling guidelines (See Table 1) are based on a constant Strouhal number for data at the same Mach number and Reynolds number. Wind tunnels with free-stream turbulence levels ($\Delta PRMS/\overline{P}$) or less than 0.5% (based on a frequency range of 0 to 4000 Hz) should be used when available. Consideration should be given to the test configuration to account for the interactive effects of the propulsion system components.

TABLE 1 - Data Scaling Guidelines, Strouhal Number Constant
(Same Reynolds Number and Mach Number)

• Frequency (Strouhal Number)	$\left.\frac{fL}{\sqrt{T}}\right)_{\text{full scale}}$	$= \left.\frac{fL}{\sqrt{T}}\right)_{\text{model scale}}$
• Record length and time delay	$\left.\frac{\tau\sqrt{T}}{L}\right)_{\text{full scale}}$	$= \left.\frac{\tau\sqrt{T}}{L}\right)_{\text{model scale}}$
• Power spectra	$\left.\frac{\phi(f)\sqrt{T}}{P^2\ L}\right)_{\text{full scale}}$	$= \left.\frac{\phi(f)\sqrt{T}}{P^2\ L}\right)_{\text{model scale}}$
• RMS values	$\left.\frac{\Delta PRMS}{\overline{P}}\right)_{\text{full scale}}$	$= \left.\frac{\Delta PRMS}{\overline{P}}\right)_{\text{model scale}}$
• Covariances	$\left.\frac{C(\tau)}{P^2}\right)_{\text{full scale}}$	$= \left.\frac{C(\tau)}{P^2}\right)_{\text{model scale}}$

7.2 Total-Pressure Instrumentation:

Recommended total-pressure instrumentation requirements for measuring steady-state and time-variant data are given below in terms of axial location, probe distribution at the inlet/engine aerodynamic interface plane, and transducer characteristics.

7.2.1 Inlet/Engine Aerodynamic Interface Plane (AIP): The instrumentation plane used to define distortion and performance at the aerodynamic interface between the inlet and the engine should be agreed upon by all involved parties. The interface should remain invariant throughout the propulsion system life cycle for all testing - sub-scale, full-scale, and flight test.

The following guidelines are suggested for selection of the physical location of the interface plane:

a. The AIP should be located in a circular or annular section of the inlet duct.
b. The AIP should be located as close as practical to the engine-face plane. The engine-face plane is defined by the leading edge of the most upstream engine strut, vane, or blade row.
c. The AIP should be located so that all engine airflow, and only the engine airflow, passes through it. The distance between the inlet auxiliary air systems and the AIP should be such that the effect of the auxiliary air systems on distortion is included in the measurements at the AIP.
d. The AIP location should be such that engine performance and stability are not measurably changed by interface instrumentation.

7.2.2 Rake/Probe Array: A probe array should be agreed to among the involved parties and should remain invariant throughout the propulsion system life cycle for all testing. A typical array for measuring inlet recovery and distortion is eight equiangularly spaced rakes with five probes per rake location at the centroids of equal areas (See Figure 2).

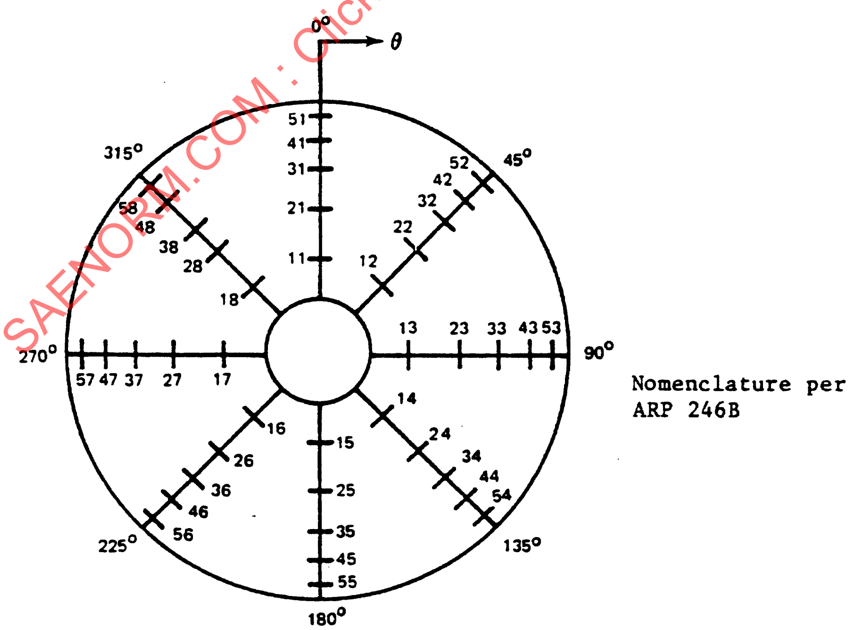

FIGURE 2 - Probe Orientation - View Looking Forward

7.2.3 Probe/Transducer Characteristics: The diameter of the probe/transducer configuration should be chosen to insure that spatial averaging of the flow unsteadiness does not significantly compromise the fidelity of the data at the highest frequency of interest. For sub-scale tests, the highest frequency of interest may be determined according to the scaling guidelines, which are given in Table 1. The natural frequency of the transducer should be in excess of ten times the highest frequency of interest. The design of the probe/transducer configuration should be influenced by the flow angularity range that the probe is likely to experience.

The frequency response characteristics of the probe/transducer combination should be determined with reference to system accuracy (See 7.3.2).

7.3 Data Acquisition:

7.3.1 Data Record Length: Time-variant data-recording lengths of 30 to 60 seconds are recommended for stabilized, full-scale data. Shorter times should be used for scale-model data acquisition, based on the scaling guidelines of Table 1. Recording lengths should be sufficient to determine whether statistically stationary data criteria are met. Time-variant data should be recorded continuously during inlet/engine/aircraft transients of interest.

7.3.2 System Accuracy: System accuracy requirements are established by the evaluation of the effect of steady-state and/or time-variant distortion on stability and performance. Overall system accuracy should be agreed on by the parties involved.

Individual steady-state pressures (signals time-averaged to attenuate frequencies greater than 0.5 Hz) should be recovered with an error not to exceed ±0.5% (± two standard deviations) of the absolute pressure being measured. Individual dynamic absolute pressures (containing data to at least the highest frequency of interest) should be recovered with an error not to exceed ±2.0% (± two standard deviations) of the absolute pressure being measured for stability and ±5.0% (± two standard deviations) for performance. These errors include all errors introduced by the sensing, recording, playback, and processing systems from the point where the pressure signal is being measured to the point where it again appears as an output pressure.

Current practice indicates that these accuracy levels are attainable if the data system is carefully developed, with appropriate experience and calibration procedures being employed.

7.3.3 System Frequency Response: The maximum frequency recorded should be agreed upon by all involved parties.

7.4 Data Processing:

7.4.1 Data Averaging or Filtering: The data filtering technique should be based on engine characteristics. For scale-model tests, frequencies should be scaled by the guidelines of Table 1.

7.4.2 Data Editing: Data editing should include procedures for identifying erroneous signals and subsequently replacing them through analytical techniques based on adjacent probes.

Edited data should be identified to differentiate it from non-edited data.

7.4.3 Data Qualification: If more than five probes of the suggested array at random locations or if three contiguous probes are not properly functioning, distortion descriptor levels computed from pressure data should be appropriately identified.

7.5 Data Transmittal:

7.5.1 Analog Data: As a minimum, the following should be satisfied when data are transmitted through a signal recorded on multiplex or multichannel magnetic tape:

a. The multiplexing system should be a constant-bandwidth system, so selected as to ensure compatibility among users. This includes specifying the number of channels per track, center frequencies, bandwidths.
b. The recording speed should be specified.
c. The tape should contain an IRIG standard tape-speed servo signal. Each multiplex group should contain a tape-flutter compensation signal. A time code signal should be recorded compatible with the time resolution requirement of the maximum data frequency of interest.
d. A table should be included which identifies the content of each tape channel and the corresponding calibration data required to reduce the signal to engineering units. An AC calibration signal should be included as well as the more usual DC calibration signal.
e. Each data record must include complete identification and, as a minimum must contain test point number, date, and facility identification.

7.5.2 Digital Data: Digital data should be transmitted in accordance with the guidelines set forth in ARP1210.

8 TERMINOLOGY:

The following terms are given to supplement definitions presented elsewhere in the text of ARP1420.

8.1 Aerodynamic Interface Plane (AIP):

An AIP is an instrumentation plane used to define inlet distortion and performance (See 7.2.1).

8.2 Distortion Descriptor:

A distortion descriptor is a non-dimensional numerical representation of the measured inlet pressure distribution (See Section 4).

8.3 Distortion Extent:

The distortion extent refers to the circumferential arc size of a distorted region (See 4.1.1.2 and Appendix, Equation A1).

8.4 Distortion Intensity:

Distortion intensity refers to the amplitude of a distortion pattern. For a circumferential distortion, intensity is defined in 4.1.1.1 and Appendix, A.1.1. For a radial distortion, intensity is defined in 4.1.2 and Appendix, A.1.2.

8.5 Distortion Sensitivity:

Distortion sensitivity is loss in compressor surge pressure ratio, ΔPRS, per unit of numerical distortion descriptor (See Appendix, Equation A12).

8.6 Inlet Flow Distortion:

Inlet flow distortion refers to spatial variations in the total pressure at the inlet-engine interface plane (See Section 4).

8.7 Loss in Surge Pressure Ratio (ΔPRS):

The loss in surge pressure ratio is the percent change in surge pressure ratio, at constant corrected airflow, between the undistorted surge line and the distorted surge point (See 5.2 and the Appendix, Equation A12).

8.8 Multiple-per-Revolution Distortion:

Multiple-per-Revolution distortion refers to the equivalent number of distorted regions occurring in 360° (See 4.1.1.3 and Appendix, A.1.1.2).

8.9 Operating Point:

An operating point refers to the location on a compressor map that satisfies the matching relationships which govern the engine operation. Operating points may describe either steady or transient operation (See Figure 1).

8.10 Performance Assessment:

Performance assessment is the procedure used to account for inlet distortion effects on engine performance (See 5.4).

8.11 Stability Assessment:

Stability assessment is the procedure by which destabilizing effects are accounted for in an engine (See 5.3).

8.12 Stall:

Stall is a flow breakdown at one or more compressor blades.

8.13 Steady-State Distortion:

Steady-state distortion is the spatial distortion measured by low-response pressure instrumentation (See Section 4, 5.4, and 7.3.2).

8.14 Surge:

Surge is a response of the entire engine which is characterized by a flow stoppage or reversal in the compression system (See 5.1).

8.15 Surge Line:

Surge line is defined by the locus of surge points on a compressor map (See Figure 1).

8.16 Surge Margin:

Surge margin is the pressure ratio range, at a constant corrected airflow, through which a compressor may be operated between its operating point and surge line without surge (See 5.1).

8.17 Surge Point:

A surge point is that point on a compressor map at the limit of stable operation defined by the maximum pressure ratio at a given airflow (See Figure 1).

8.18 Time-Variant Distortion:

Time-variant distortion is the spatial distortion measured by high-response total-pressure instrumentation.

APPENDIX A

A.1 CALCULATION OF DISTORTION ELEMENTS:

Inlet spatial distortion is described in terms of the circumferential and radial elements.

A.1.1 Circumferential Distortion Elements:

Circumferential distortion is described on a ring-by-ring basis in terms of intensity, extent, and multiple-per-revolution elements. The intensity or level of distortion is a numerical indication of the magnitude of the pressure distortion. The extent element is a numerical indication of the circumferential size of the low-pressure region. The multiple-per-revolution element is a numerical indication of the equivalent number of circumferential regions of low pressure.

A.1.1.1 One-Per-Rev Patterns: The “intensity” and “extent” elements of circumferential distortion are obtained by linear interpolation of the pressures in a given instrumentation ring. Figure A1 shows typical pressures for the probes in the i-th ring for a one-per-revolution pattern (one pressure defect in 360°). Theta minus, θ_i^-, is the circumferential extent of the low-pressure region. It is defined by the intersection between the ring average pressure and the linear interpolation which subtends the low-pressure region.

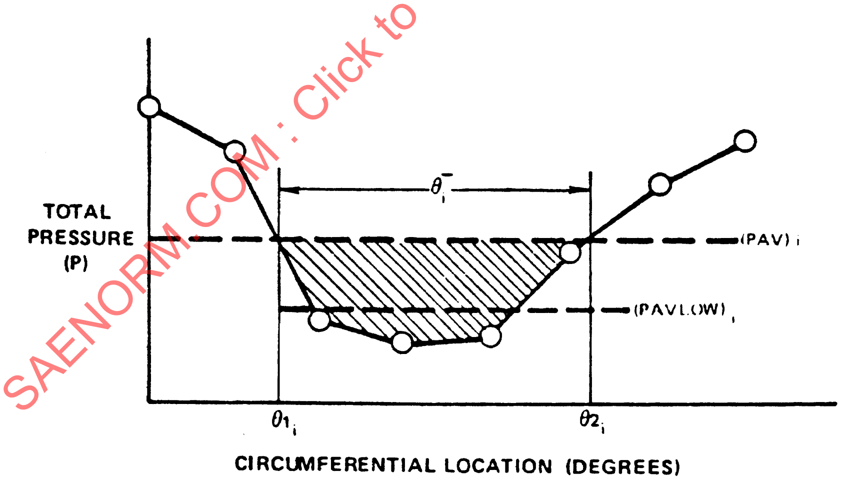

FIGURE A1 - Ring Circumferential Distortion for a One-Per-Rev Pattern