



AEROSPACE RECOMMENDED PRACTICE

ARP6420™

Issued

2021-01

Guidelines for Characterization of Gas Turbine Engine
Total-Pressure, Planar-Wave, and Total-Temperature Inlet-Flow Distortion

RATIONALE

The SAE S-16 Turbine Engine Inlet Flow Distortion Committee has developed an Aerospace Recommended Practice (ARP) and Aerospace Information Reports (AIR) describing measurement stations and techniques, and descriptors for different types of inlet total-pressure, planar-wave, and total-temperature distortion. There has been broad acceptance of these descriptors by the industry. Although a treatment for swirl distortion has been proposed, no methodology for swirl distortion has gained wide acceptance. When an accepted methodology exists for swirl distortion, this document will be updated to include it. This document provides a single source that contains the recommended measurement stations and techniques, and descriptors for total-pressure, planar-wave, and total-temperature inlet distortion.

FOREWORD

The most important consideration for successful correlation of data is consistency throughout the ground and flight test programs. Consistency of instrumentation and data reduction techniques should be maintained throughout the test program. The physical layout of the Aerodynamic Interface Plane (AIP), data acquisition, filtering techniques, and data reduction processes should all be agreed upon by all parties (certifying agencies, airframers, engine manufacturers, and ground and flight test organizations) and should be invariant throughout the program. The program should consider the ultimate goals of testing, flow physics, and flow fields being evaluated when designing an air vehicle test program.

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1. SCOPE

The turbine-engine-inlet flow distortion descriptors summarized in this document apply to the effects of inlet total-pressure, planar-wave, and total-temperature distortions. Guidelines on stability margin, destabilizing influences, types and purposes of inlet data, AIP definition, and data acquisition and handling are summarized from AIR5866, AIR5867, ARP1420, and AIR1419. The degree to which these recommendations are applied to a specific program should be consistent with the complexity of the inlet/engine integration. Total-pressure distortion is often the predominant destabilizing element that is encountered and is often the only type of distortion to be considered, i.e, not all types of distortion need to be considered for all vehicles.

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 International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1419	Inlet Total-Pressure-Distortion Considerations for Gas-Turbine Engines
AIR5686	A Methodology for Assessing Inlet Swirl Distortion
AIR5687	Inlet/Engine Compatibility - From Model to Full Scale Development
AIR5866	An Assessment of Planar Waves
AIR5867	Assessment of the Inlet/Engine Temperature Distortion Problem
AIR6345	Processing and Validating CFD Data for Estimating Inlet Dynamic Total-Pressure Distortion
ARP1420	Gas Turbine Engine Inlet Flow Distortion Guidelines

2.1.2 Other Applicable Documents

- 2.1.2.1 Lytle, J., "The Numerical Propulsion System Simulation: An Overview," NASA TM-2000-209915, NASA Glenn Research Center, June 2000.
- 2.1.2.2 Steenken, W., "Planar Wave Stability Margin Loss Methodology," AIAA 1988-3264, AIAA/ASME/SAE/ASEE 24th Joint Propulsion Conference, Boston, Massachusetts, July 11-13, 1988.
- 2.1.2.3 "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations," AIAA G-077-1998.
- 2.1.2.4 Babcock, D. and Mani, M., "BCFD Predictions of Steady-State and Dynamic Distortion for the 3rd AIAA Propulsion Aerodynamics Workshop," AIAA 2017-4836, July 2017.
- 2.1.2.5 Brimelow, B., Collins, T., and Pfefferkorn, G., "Engine Testing in a Dynamic Environment," AIAA 1974-1198, AIAA/SAE 10th Propulsion Conference, San Diego, CA, Oct. 21-23, 1974.
- 2.1.2.6 Plourde, G. and Brimelow, B., "Pressure Fluctuations Cause Compressor Instability," Proceedings of the Air Force Airframe-Propulsion Compatibility Symposium, AD0876608, June 1970.

- 2.1.2.7 Jacocks, J. and Kneile, K., "Statistical Prediction of Maximum Time-Variant Inlet Distortion Levels," AEDC-TR-74-121.
- 2.1.2.8 Tanguy, G., MacManus, D., Garnier, E., and Martin, P., "Characteristics of Unsteady Total-pressure Distortion for a Complex Aero-engine Intake Duct," Aerospace Science and Technology 78, 2018.
- 2.1.2.9 Arend, D. and Saunders, J., "An Experimental Evaluation of the Performance of Two Combination Pitot Pressure Probes," NASA TM-2009-215632.

2.2 Definitions

ELEMENT(S): Circumferential- and radial-distortion elements are non-dimensional numerical representations of distortion at the AIP, described on a ring-by-ring basis. There are four fundamental total-pressure-distortion elements defined in ARP1420 including the circumferential distortion intensity ($\Delta PC/P$), circumferential distortion extent (θ°), circumferential distortion multiple-per-revolution content (MPR), and radial distortion intensity ($\Delta PR/P$). Similar elements are also defined for total-temperature distortion in AIR5867. Other ring-by-ring basis elements can be defined.

DESCRIPTOR(S): Descriptors are non-dimensional numerical representations describing inlet distortion levels at the AIP, using some combination of ring-based distortion elements. There can be any number of distortion descriptors defined including, for example, two-ring or five-ring averages of the circumferential pressure-distortion intensity ($\Delta PC/P$), or two-ring averages of the radial pressure-distortion intensity ($\Delta PR/P$).

CORRELATION(S): Correlations are non-dimensional numerical equations having a unique combination of weighted distortion descriptors. The weightings are empirical sensitivities relating the loss of compression component stability-pressure ratio to inlet distortion. One such example is loss of stability-pressure ratio due to total-pressure distortion, ΔPRS , given by Equation A9 of ARP1420.

2.3 Symbols

C	Constant that relates the root-mean-square of the loss of stability pressure ratio to the maximum loss of stability pressure ratio
C_i	Offset term for ring i (empirically determined)
CT_i	Offset term for ring i (empirically determined)
$C(\tau)$	Covariance
f	Frequency over the range of interest
f_r	Frequency, full scale
f_m	Frequency, model scale
F	Maximum frequency of interest
i	Ring number
j	Rake number
KC_i	Circumferential total-pressure-distortion sensitivity of ring i (empirically determined)
K_{PW}	Component sensitivity to planar waves
KR_i	Radial total-pressure-distortion sensitivity of ring i (empirically determined)
KTC_i	Circumferential total-temperature-distortion sensitivity of ring i (empirically determined)

KTR_i	Radial total-temperature-distortion sensitivity of ring i (empirically determined)
L	Characteristic length
l_f	Characteristic length, full scale
l_m	Characteristic length, model scale
MPR_i	Multiple-per-rev element
N	Number of rings
P	Pressure
$\bar{P}$	Mean (time-averaged) total pressure at the AIP
$\hat{P}_{PEAK}$	Maximum peak-to-peak pressure ratio of planar wave
$\hat{P}_{RMS}$	Root-mean-square pressure ratio of a planar wave
$\hat{P}(t_k)$	Non-dimensional time-dependent planar wave at time t_k
PAV_i	Ring i average total pressure
$PAVLOW_i$	Average low total pressure in ring i
$P_i(\theta)$	Function resulting from a linear fit between points of ring i total pressures
$PR1$	Undistorted flow stability-limit-line total-pressure ratio
$PRDS$	Distorted flow stability-limit-line total-pressure ratio
PRO	Operating-line total-pressure ratio
$R(i)$	Radius of ring i
R_{in}	Hub radius
R_{out}	Outer radius
SM	Stability margin
T	Temperature
$T_{0,A,f}$	Ambient air and exhaust gas mixture total temperature at equivalent cross-sections A , full scale
$T_{0,a,f}$	Ambient total temperature, full scale
$T_{0,a,m}$	Ambient total temperature, model scale
$T_{0,e,f}$	Exit total temperature, full scale
$T_{0,e,m}$	Exit total temperature, model scale
$T_{a,f}$	Ambient temperature, full scale
$T_{a,m}$	Ambient temperature, model scale

TAV_i	Ring i average total temperature
$TAVH_i$	Average high total temperature in ring i
$TFAV$	Compressor face average temperature
$T(\theta)_i$	Function resulting from a linear fit between points of ring i temperatures
t_f	Time, full scale
t_m	Time, model scale
$U_{a,f}$	Ambient velocity in the axial direction, full scale
$U_{a,m}$	Ambient velocity in the axial direction, model scale
$U_{e,f}$	Exit velocity in the axial direction, full scale
$U_{e,m}$	Exit velocity in the axial direction, model scale
$U_{i,f}$	Inlet velocity in the axial direction, full scale
$U_{i,m}$	Inlet velocity in the axial direction, model scale
$\left(\frac{\Delta PC}{P}\right)_i$	Circumferential total-pressure distortion intensity of ring i
$\left(\frac{\Delta PR}{P}\right)_i$	Radial total-pressure distortion intensity of ring i
$\Delta PRMS$	Change in root-mean-square total pressure
ΔPRS	Loss of stability pressure ratio
ΔSM	Loss of stability margin
$\left(\frac{\Delta TC}{T}\right)_i$	Circumferential total-temperature distortion intensity of ring i
$\left(\frac{\Delta TR}{T}\right)_i$	Radial total-temperature distortion intensity of ring i
θ	Circumferential angle around ring measured from top dead center, degrees
θ_i^+	Circumferential extent of largest region of ring i with temperature above ring i average, degrees
θ_i^-	Circumferential extent of largest region of ring i with pressure below ring i average, degrees
θ_{ik}^-	Circumferential extent of k th region of ring i with pressure below ring i average, degrees
$\rho_{a,f}$	Ambient density, full scale
$\rho_{a,m}$	Ambient density, model scale
$\rho_{e,f}$	Exit density, full scale
$\rho_{e,m}$	Exit density, model scale

τ	Lag time, seconds
φ	Power spectral density of the waveform formed by the spatial average of the AIP non-dimensional total-pressure waveform at each time step

3. STABILITY MARGIN

Quantitative evaluations of compression-component stability are necessary to provide technical visibility relative to target levels during engine development programs. This is accomplished by using the following definitions to quantify the available stability margin and applicable compression-component destabilizing influences. Test data are required inputs to the stability margin calculations.

The available stability margin for a specific compression component at a given corrected airflow is defined as the difference between the clean-inlet-flow stability-limit-line total-pressure ratio and the operating-line total-pressure ratio non-dimensionalized by the operating line total-pressure ratio. In numerical terms with reference to Figure 1:

$$SM = \left(\frac{PR1 - PRO}{PRO} \right) \times 100 \quad (\text{Eq. 1})$$

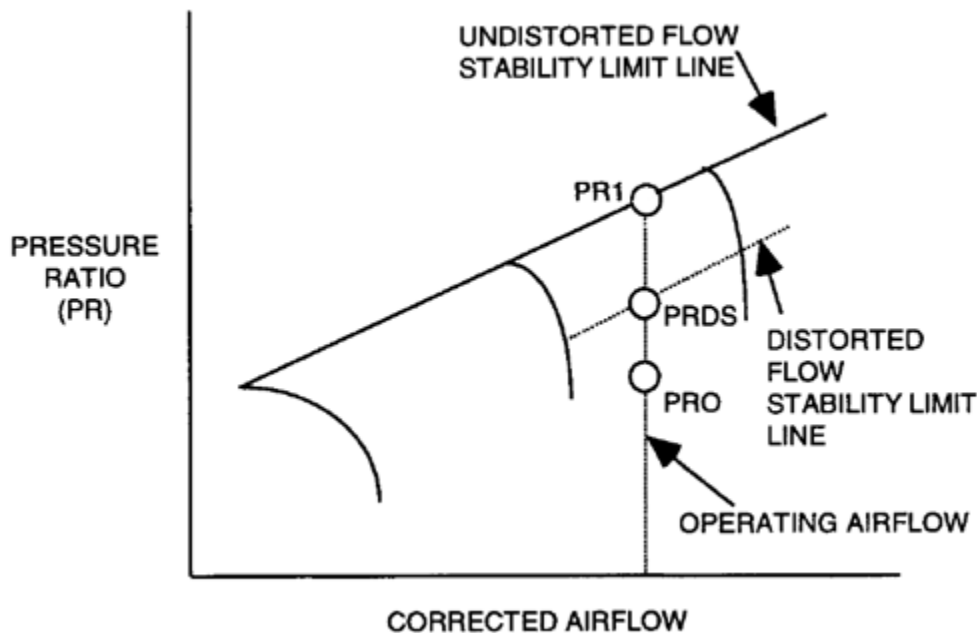


Figure 1 - ARP1420 stability margin definition

The loss of stability pressure ratio is defined as the decrease in total-pressure ratio relative to the stability-limit-line total-pressure ratio non-dimensionalized by the stability-limit-line total-pressure ratio, all at constant corrected airflow. Numerically and with reference to Figure 1, it is defined as:

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

The loss in stability pressure ratio as it relates to available stability margin is defined as the decrease in total-pressure ratio relative to the undistorted stability limit line total-pressure ratio non-dimensionalized by the operating line total-pressure ratio, all at constant corrected airflow. Numerically and with reference to Figure 1, it is defined as:

$$\Delta SM = \left(\frac{PR1 - PRDS}{PRO} \right) \times 100 \quad (\text{Eq. 3})$$

4. STABILITY ASSESSMENTS

Assessments should be carried out regularly and in increasing detail throughout the development and life cycles of a propulsion system. A stability assessment provides quantitative estimates of the effects of inlet distortion and other destabilizing influences on compression-component stability. The assessment should be performed in a manner to reveal the stability margin usage by accounting for the factors that lower the compression-component stability limit line and/or raise the compression-component operating line. The assessment, performed at constant corrected engine airflow (the matched inlet-engine corrected airflow at the steady-state operating point corresponding to the propulsion-system operating condition being investigated), requires that compression-component stability limit lines be defined over the entire corrected-airflow operating range for each compression component.

Factors to be considered, if appropriate, include external destabilizing factors and internal destabilizing factors. External destabilizing factors can include but are not limited to time-variant inlet total-pressure distortion, planar waves (in-phase total-pressure oscillations), time-variant inlet total-temperature distortion, inlet swirl distortion, and exit static-pressure distortion. Internal destabilizing factors can include but are not limited to component interactions, deterioration, component variation due to manufacturing tolerances, control tolerances, variable-geometry position, power-lever transients, operating-point shift with distortion, Reynolds number effects, compression component bleed, intra-compression component bleed, and horsepower extraction.

The effect of each factor is expressed as a change in stability margin. The loss in stability margin for the external destabilizing factors is computed from the distortion-descriptor elements and their respective sensitivities, which are then combined for each type of distortion. Some effects of factors are cumulative and should be added algebraically, whereas other effects of factors are random and should be added statistically (ARP1420, AIR1419). The method and rationale for combining individual effects should be delineated and supported by test experience.

Total-pressure distortion transfer coefficients and total-temperature generation coefficients are used to transfer inlet-distortion effects to the downstream compression components. Stability assessments are made for each compression component.

Stability assessments should be conducted at the Mach numbers, altitudes, airflows, and engine operating and maneuver conditions (angles of attack and sideslip) necessary for performance and operability verification, including the appropriate inlet recovery and the effects of any compression-component rematch.

5. TESTING

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

5.1 Test Planning

A master test plan should be developed early in the program. This 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.

5.1.1 Testing Scope

Tests that may be required prior to production will depend on the propulsion system under development. The types of test and test objectives follow.

5.1.2 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.

5.1.3 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, bleed effects, Reynolds number effects, component interactions, engine performance, and stability evaluation. Stability data should be obtained whenever practical.

5.1.4 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.

5.2 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:

- a. Inlet: Inlet configuration details, mass flow ratio, corrected airflow, Reynolds number, Mach number, aircraft angles of attack and sideslip, and bleed flows
- b. Engine: Engine configuration details, operating corrected speeds, corrected airflow, bleed flows, power extraction requirements, control function (steady-state or transient), operating mode (afterburning, non-afterburning, etc.), compressor-face total pressure and total temperature, and compressor inlet total-pressure distortion pattern (probe values)

Engine tests provide data for verification of stability assessment line items, stability audit methodology at critical flight points, stability demonstration, and documentation. Compressor stability-limit-line and stability-margin utilization data together with compressor speed, compressor airflow, 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 stability pressure ratio should be accomplished whenever practical. Stability data for the stability assessment can 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 stability 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.

If distortion effects are demonstrated to have a strong effect on thrust, then the sensitivity must be determined.

6. TYPES OF DISTORTION

In the following subsections, the equations for the distortion elements for total-pressure, planar-wave, and total-temperature distortions are provided. The total-pressure, planar-wave, and total-temperature distortion elements are developed from measurements made using a ring-rake array located at the AIP (see Section 7).

6.1 Total-Pressure Distortion

The equations and figures defining the total-pressure distortion elements are described in the sections below. Additional information about total-pressure distortion can be found in ARP1420 and AIR1419.

Total-pressure distortion can be described as a spatial variation in total pressure at the AIP. There are both steady-state and time-variant (dynamic) components of total-pressure distortion. Steady-state total-pressure distortion is the spatial variation in time-averaged total pressure across the AIP. Time-variant total-pressure distortion is determined from measurements of total pressure using high-response pressure sensors located at a number of locations at the AIP. The peak distortion pattern that is present for a time period that could cause a destabilizing engine response, typically on the order of one-half to one rotor revolution, represents the peak, e.g., destabilizing, total-pressure distortion.

6.1.1 Stability Pressure-Ratio-Loss Correlation

The loss of stability pressure ratio due to total-pressure distortion, expressed as a percent of the undistorted stability pressure ratio, is determined using the distortion correlation, ΔPRS , as expressed in Equation 4. Total-pressure distortion is described in terms of circumferential and radial distortion elements.

$$\Delta PRS = \sum_{i=1}^N \left[KC_i \times \left(\frac{\Delta PC}{P} \right)_i + KR_i \times \left(\frac{\Delta PR}{P} \right)_i + C_i \right] \times 100 \quad (\text{Eq. 4})$$

where the distortion elements are:

N = number of instrumentation rings

KC_i = circumferential total-pressure distortion sensitivity of ring i (empirically determined)

KR_i = radial total-pressure distortion sensitivity of ring i (empirically determined)

$(\Delta PC/P)_i$ = circumferential total-pressure distortion intensity of ring i defined in Equation 6

$(\Delta PR/P)_i$ = radial total-pressure distortion intensity of ring i defined in Equation 16

C_i = offset term for ring i (empirically determined)

6.1.2 Total-Pressure Distortion Elements

The equations and figures defining the total-pressure distortion elements appear in the sections below.

The Aerodynamic Interface Plane (AIP, defined and described in Section 7) total-pressure probe data are used to describe inlet total-pressure distortion directly in terms of the instantaneous total-pressure contours (pattern) and numerically in terms of distortion descriptors that are related to the severity of the distortion. Distortion descriptors provide a means of identifying critical distorted inlet-flow conditions and of communicating during propulsion system development and life cycles. Distortion elements have been identified for use in creating a distortion sensitivity correlation for a particular engine. These elements are combined to define each distortion descriptor system. The distortion elements are used to quantify the distortion at the AIP. Fundamental to the distortion elements is the set of total pressures that are used to describe the total-pressure distribution. The total-pressure probes usually are arranged in rake and ring arrays. Circumferential- and radial-distortion elements, which are calculated using the total-pressure probe measurements, are defined on a ring-by-ring basis. Inlet spatial distortion is described in terms of circumferential and radial elements and is discussed in detail in the following paragraphs.

Circumferential distortion is described for each instrumentation ring in terms of intensity, extent, and multiple-per-revolution elements.

- a. Intensity: The circumferential distortion intensity element $(\Delta PC/P)$ is a numerical indication of the magnitude of the total-pressure defect for each ring.
- b. Extent: The circumferential distortion extent element (θ^-) is the angular region, in degrees, in which the total pressure is below the ring-average total pressure.
- c. Multiple-per-Revolution: The circumferential distortion multiple-per-revolution element (MPR) is a numerical indication of the “effective” number of low total-pressure extents for each ring.