



AEROSPACE INFORMATION REPORT

AIR6345™

Issued

2020-10

Processing and Validating CFD Data
for Estimating Inlet Dynamic Total-Pressure Distortion

RATIONALE

Progress is being made in Computational Fluid Dynamic (CFD) methods for correlating with experimental results for internal aerodynamics such as inlet steady-state total-pressure recovery and distortion. Development efforts are focusing on time-accurate CFD technology to estimate inlet peak-dynamic distortion. Validated solutions from CFD tools must be demonstrated to warrant use in official turbine-engine stability audits and/or for selecting worst-case distortion patterns for engine-qualification test demonstrations. This document presents procedures for processing time-dependent total-pressure records from test and CFD, along with approaches for validating time-dependent CFD results used to estimate inlet dynamic-flow distortion.

NOTICE

This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user. This document has been cleared for public release per Case Number 88ABW-2020-2112.

PREFACE

The report is based on experiences of the SAE S-16 Turbine Engine Inlet Flow Distortion Committee members who collectively have used experimental data or time-dependent CFD models to determine random fluctuations of total pressure associated with turbulent flows in aircraft inlet systems. Because of the rapid growth in this use of such CFD models, there is interest in providing the CFD community with recommendations from the S-16 Committee for validating such CFD results so that they may be used in inlet-system design or turbine-engine stability audits. Since the flow physics of interest are random, the recommended validation procedures use descriptive and inferential statistics of time-series samples. Users of these procedures are expected to have resources, i.e., training, textbooks, or subject-matter experts, available to aid in understanding and applying these statistical procedures (References 2.2.1 and 2.2.2).

SAE Technical Standards Board Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2020 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
<http://www.sae.org>

SAE WEB ADDRESS:

Full document details: SAE AIR6345

For more information on this standard, visit
<https://www.sae.org/standards/content/AIR6345>

Documents
Document Sharing Hub

TABLE OF CONTENTS

1.	SCOPE.....	3
1.1	Purpose	3
2.	REFERENCES.....	3
2.1	Applicable Documents	3
2.1.1	SAE Publications.....	3
2.2	Related Publications	3
2.3	Abbreviations and Symbols	4
2.3.1	Abbreviations List.....	4
2.3.2	Symbol List.....	5
2.4	Definitions	6
3.	BACKGROUND	6
4.	OVERVIEW OF VALIDATION PROCESSES.....	9
5.	PROCESSING AND VALIDATION OF CFD-BASED TIME-DEPENDENT TOTAL-PRESSURE DATA ...	11
5.1	Processing of Time-Dependent Total-Pressure Data	11
5.2	Validation of CFD-Based Total-Pressure Data	16
5.2.1	Amplitude Domain Equivalence	16
5.2.2	Time and Space Domain Equivalence	19
6.	PROCESSING AND VALIDATING CFD-BASED DYNAMIC TOTAL-PRESSURE DISTORTION	23
6.1	Background on Procedures for Determining Peak Distortion	23
6.2	Validating Dynamic Distortion and Identifying Peak Total-Pressure Distortion	24
6.3	Assessing the Accuracy of CFD-Based Peak Total-Pressure Distortion Data	28
7.	EXPERIMENTAL DATA SETS FOR VALIDATION OF CFD RESULTS	29
8.	SUMMARY AND RECOMMENDATIONS.....	29
9.	NOTES	30
9.1	Revision Indicator.....	30
Figure 1	Contours of steady-state and dynamic total-pressure distortion.....	7
Figure 2	Typical subscale inlet model, AIP total-pressure array, and probe	8
Figure 3	Processes for validation of CFD dynamic total-pressure data and distortion	10
Figure 4	Demonstration of weak statistical stationarity	14
Figure 5	Characteristics of Q-Q plot for equivalent and different distributions	17
Figure 6	Example Q-Q plot for validating the amplitude domain of probe CFD recovery.....	19
Figure 7	CFD and test auto-correlation coefficients for probe data	20
Figure 8	Typical ring/rake probes for amplitude probability density and auto-correlation analyses	21
Figure 9	Cross-correlation coefficient for data on two adjacent probes.....	22
Figure 10	Example pairs of ring/rake probes for cross-correlation analyses	22
Figure 11	Segments of original and filtered total-pressure waveforms.....	25
Figure 12	Time history of DPCPave indicating peak DPCPave distortion.....	26
Figure 13	Total-pressure patterns of steady-state and peak DPCPave distortion descriptor.....	27
Table 1	Steps leading up to acquisition of dynamic total-pressure data.....	13
Table 2	Steps for acquiring dynamic total-pressure data	15
Table 3	Steps leading to determining peak dynamic distortion	27

1. SCOPE

The processes addressed in this Aerospace Information Report (AIR) apply to the acquisition and validation of dynamic total-pressure and distortion data from CFD models simulating turbulent flows in inlets. The results of these processes can be used in the formation of an inlet-flow-distortion methodology that addresses turbine-engine operability assessments.

1.1 Purpose

This Aerospace Information Report (AIR) provides processes for acquiring and analyzing dynamic total-pressure distortion data from CFD simulations in order to assess the quality of CFD-based solutions relative to appropriately collected experimental data.

2. REFERENCES

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 Applicable Documents

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 Total Temperature Distortion Problem
ARP1420	Gas Turbine Engine Inlet Flow Distortion Guidelines

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

- 2.2.1 Walpole, R., Myers, R., Myers, S., and Ye, K., "Probability & Statistics for Engineers & Scientists," 9th Ed., Princeton Hall, New Jersey, 2012.
- 2.2.2 Bendat, J. and Piersol, A., "Random Data: Analysis and Measurement Procedures," John Wiley and Sons, 1971.
- 2.2.3 Plourde, G. and Brimelow, B., "Pressure Fluctuations Cause Compressor Instability," Airframe/Propulsion Compatibility Symposium, AFAPL-TR-69-103, June 1969.
- 2.2.4 Winkler, C. and Davis, Z., "Summary of the 3rd Propulsion Aerodynamics Workshop: S-duct Results," AIAA 2017-4912, July 2017.

- 2.2.5 Mace, J., Lakebrink, M., Mani, M., and Steenken, W., "Computational Simulation of Dynamic Total-Pressure Distortion in an S-Diffuser," AIAA 2012-3999, July 2012.
- 2.2.6 AIAA, "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations," AIAA-G-077-1998, Reston, VA, 1998.
- 2.2.7 Oberkampf, W. L. and Trucano, T. G., "Validation Methodology in Computational Fluid Dynamics," AIAA 2000-2549, June 2000.
- 2.2.8 Lee, H. B., et al., "Development and Use of Engineering Standards for Computational Fluid Dynamics for Complex Aerospace Systems," AIAA 2016-3811, June 2016.
- 2.2.9 Mace, J., Steenken, W., Winkler, C., and Harvell, J., "Validation Approach for CFD-Based Random Total-Pressure Data," AIAA 2020-0346, January 2020.
- 2.2.10 Steenken, W. G., "Effect of Transducer Diameter on Resolution of Total Pressure Fluctuations in a Turbulent Flow," Progress in Astronautics and Aeronautics, Instrumentation for Airbreathing Propulsion, Edited by Allen E. Fuhs and Marshall Kingery, MIT Press, Volume 34, 1974.
- 2.2.11 Kravchenko, A. G. and Moin, P., "On the Effect of Numerical Errors in Large Eddy Simulations of Turbulent Flows," J. Comp. Physics, 131, pp. 310-322, 1997.
- 2.2.12 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.
- 2.2.13 Pope, S., "Turbulent Flows," Cambridge University Press, 2012.
- 2.2.14 McMillan, M., et al., "Inlet Flow Control and Prediction Technologies for Embedded Propulsion Systems," NASA CR 2011-217237, Dec. 2011.

2.3 Abbreviations and Symbols

2.3.1 Abbreviations List

AIAA	American Institute of Aeronautics and Astronautics
AIP	Aerodynamic Interface Plane (ARP1420)
AIR	Aerospace Information Report
ARP	Aerospace Recommended Practice
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
Hz	Hertz
PDF	Probability Density Function
NASA	National Aeronautics and Space Administration
RMS	Root Mean Square
RPM	Revolutions per Minute

2.3.2 Symbol List

$C_{mn}(\tau)$	Auto ($m = n$) or Cross ($m \neq n$) Covariance Function
EXT	Extent of Circumferential Low-Pressure Distortion Region
f	Frequency [Hz]
f_{fs}	Frequency at Full Scale for Engine Compression System
f_{ms}	Frequency at Model Scale for Engine Compression System
$f_{c\text{-alias}}$	Cut-off (-3 dB) Frequency of Anti-Alias Filters
f_s	Samples per Second
i, j	Indices for Probes, e.g., $PT_{i,j}$, where i = Ring Number, j = Rake Number
k	Wave Number
m, n	Probe Identifiers Used in Correlation Coefficients (see 5.2.2)
MPR	Multiple per Revolution
N	Total Number of Probes at AIP
P_{fav}	Face-Average Total Pressure at AIP
PT	Total Pressure
PT0	Freestream Total Pressure
PT2	AIP Total Pressure
PT2ave	Averaged Total-Pressure Ratio, $PT2/PT0$, Measured or Computed over AIP
$PT2ave(i)$	Time-Averaged Total-Pressure Ratio, $PT_i/PT0$, of i^{th} Probe on AIP
$PT2(i)_{rms}$	Root-Mean-Square of Total-Pressure Ratio, $PT_i/PT0$, of i^{th} Probe on AIP
t	Time
$T_{sample_{ms}}$	Sampling Duration for Model-Scale Hardware
U_{mean}	Mean Speed of the Flow Crossing AIP
$\bar{x}$	Mean Value of Sample “x” for CFD or Test Database
α	Significance Level of a Statistical Test (i.e., Probability of Rejecting the Null Hypothesis when the Null Hypothesis Is True)
β	Probability of Accepting the Null Hypothesis when the Null Hypothesis Is False
δ	Acceptance Interval
ΔL	Length Increment
$\Delta PC/P, DPCPave$	Circumferential Distortion Intensity

$\Delta PR/P$, DPRP	Radial Distortion Intensity
ΔPRS	Stability Pressure Ratio Loss (ARP1420, Eq. A9)
ρ_{mn}	Correlation Coefficient between Probe m and Probe n
Δs	Distance Increment
τ	Time Lag
θ^*	Circumferential-Distortion Extent of Low-Pressure Region

2.4 Definitions

ELEMENT(S): Circumferential and radial distortion elements (obtained using the total pressure-probe readings) are non-dimensional numerical representations of distortion at the AIP, described on a ring-by-ring basis. There are four fundamental 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 ($\Delta PR/P$). 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 distortion intensity ($\Delta PC/P$), or two-ring averages of the radial 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 distortion, ΔPRS , given by Equation A9 of ARP1420.

3. BACKGROUND

The evolution of flow-distortion accounting techniques has made it possible to correlate the aerodynamic stability of turbine engine compressors to time-dependent total-pressure properties measured at the aerodynamic interface plane (AIP), refer to ARP1420, between the engine and the inlet systems. Historically, time-dependent total-pressure data have been experimentally obtained from wind-tunnel tests of subscale models and/or flight vehicles covering both static and maneuver conditions throughout the flight envelope of an aircraft.

Up until the mid-1960s, it was generally accepted that turbine engines responded only to steady-state total-pressure distortion¹. During the late 1960s and early 1970s, it was learned (Reference 2.2.3) that inlet flows contained regions with below-average total-pressure which varied randomly in magnitude, extent, and time. The phenomenon was referred to as dynamic² total-pressure distortion. When this type of distortion existed for a characteristic time of at least one-half to one engine rotor revolution (determined by filtering of the individual total-pressure signals used to calculate distortion), it resulted in a loss in stability pressure ratio of the compression system. As an example, a steady-state total-pressure distortion contour is contrasted with an associated dynamic total-pressure distortion contour in Figure 1. It is apparent that the loss in total pressure and the extent of the low pressure region are both larger for the dynamic distortion contour when compared with the steady-state (time-averaged) distortion contour. These adverse changes associated with dynamic distortion lead to an increased loss in stability pressure ratio of the compression system. It is important to recognize that the contours associated with dynamic total-pressure distortion are derived from random total-pressure fluctuations in a turbulent flow. Even though the exact same contour may not be observed ever again, the worst contours have been found to be similar in shape and duration for given flight and engine operating conditions. From these worst contours, a single contour is identified as a realistic estimation of the peak distortion the inlet/engine system is likely to witness in service at those conditions.

¹ Distortion refers to the spatial non-uniformity of total pressure across the AIP.

² Dynamic, as used in this document, is synonymous with high-response, time-dependent, or time-variant.

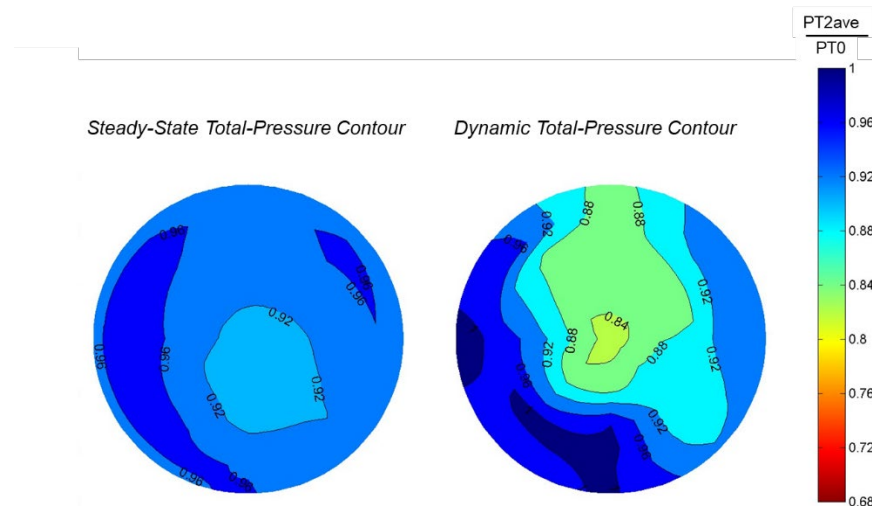


Figure 1 - Contours of steady-state and dynamic total-pressure distortion

As a result of this discovery, procedures were needed to measure the dynamic total-pressure distortion at the aerodynamic interface plane (AIP), and a methodology was required to assess their impact on the stability margin of the engine compression system. In March of 1978, an Industry/Government consensus methodology for assessing the effect of total-pressure distortion on compression-system aerodynamic stability was published as ARP1420 by the SAE S-16 Committee. A companion document, AIR1419, supplementing ARP1420 with additional information, was published in May of 1983. These documents provide guidelines for obtaining experimental data to characterize the inlet flow field from a distortion perspective. Additionally, these documents contain a description of recommended high-response pressure instrumentation and the accounting methodologies used in assessing inlet-engine compatibility.

Per the recommendation of ARP1420 and AIR1419, dynamic total pressures are measured with high-response pressure sensors to capture key flowfield characteristics. These sensors, which can measure both the steady-state, e.g., mean value, and dynamic portions of the total pressure, are typically mounted in a rake-probe array and measure total-pressure variations produced by whatever phenomena affect the AIP flow field. A high-response sensor installed in a pitot tube mounted on a rake is illustrated in Figure 2 along with the typical location of an AIP. Examples of such flow phenomena include fuselage vortices, fuselage flow separations, separated flows from protuberances (vanes and sensors), flows from boundary-layer diverters and porous bleed surfaces, shock/boundary-layer interactions, and cowl lip and diffuser flow separations.

The analog signals from the high-response total-pressure sensors are passed through anti-alias low-pass filters and are then sampled at the target sampling frequency to generate the baseline total-pressure dataset. Prior to calculation of distortion-descriptor elements, it may be necessary and appropriate to post-process filter the baseline dataset through a second digital filter designed to limit the signal frequency content to that equivalent to the compression-system stability-response frequency corresponding to 1/2 to 1 rotor revolution. Data reduction techniques then transform the data into distortion-descriptor elements which are subsequently used as inputs to calculations for estimating stability pressure-ratio loss in engine compression components. The descriptor elements (refer to ARP1420), which characterize the low total-pressure regions, are identified as circumferential distortion intensity ($\Delta PC/P$), circumferential distortion extent (θ), circumferential distortion multiple-per-revolution content (MPR), and radial distortion intensity ($\Delta PR/P$). Design practices and customer specifications require that an engine have sufficient stability margin throughout the flight and maneuver envelopes of the aircraft to prevent engine aerodynamic instability.

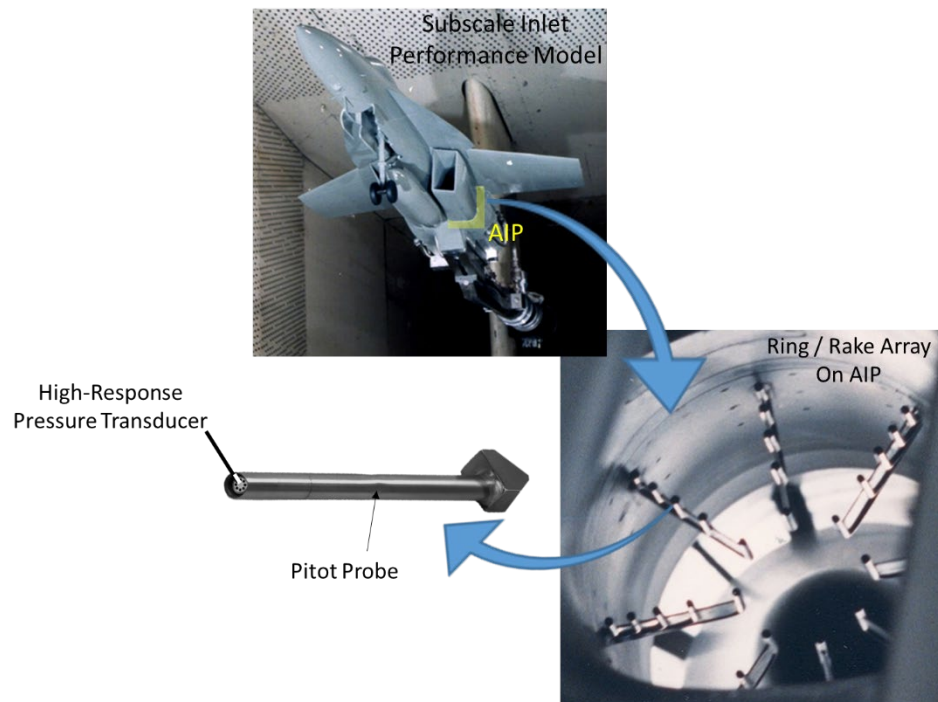


Figure 2 - Typical subscale inlet model, AIP total-pressure array, and probe

CFD technologies also have improved for computing, processing, and using both steady-state and dynamic total-pressure data to assess inlet/engine compatibility. Although no validated solutions from specific CFD models have yet been published for this purpose, there is a growing belief that CFD practices show promise in calculating steady-state total-pressure recovery and distortion (Reference 2.2.4). Steady-state CFD technology is routinely used to support the initial design of inlet systems and ground-test hardware. Furthermore, time-accurate CFD methods have matured to the point where useful information can be provided to both the inlet designers and engine operability engineers. Specifically, comparison with experimental data indicates (Reference 2.2.5) that time-accurate simulations contain large-scale turbulent-flow structures in the presence of boundary layers for more complex geometries including inlet systems. In order for CFD calculations of inlet dynamic total-pressure distortion to be used in official stability audits and/or for selecting worst-case total-pressure contour patterns for engine qualification tests, they must be rigorously validated against high-quality experimental data.

References 2.2.6, 2.2.7, and 2.2.8 have laid a framework of validation processes of CFD data. This framework is adapted herein for use in inlet-development activities and, eventually, stability audits. Inlet flows are described by nonlinear partial differential equations for conservation of mass, momentum, and energy along with their appropriate initial and boundary conditions. As used herein, a CFD model includes a difference representation of these equations, auxiliary equations such as equation of state and turbulence model, and a spatially-discretized grid system representing the solution domain. Using a numerical algorithm, the CFD model is advanced in time to produce a time-series of total-pressure data at the AIP. As the CFD model is matured, adjustments are made in modeling parameters to improve agreement with experimental data. This practice is referred to as a *calibration* process. A successful calibration process leads to a *validation* process. As defined by References 2.2.6 and 2.2.7, "validation is the process of determining the degree to which the CFD model is an accurate representation of the natural world from the perspective of the intended uses of the model." It is important to recognize that "individual computational outcomes of a model are validated; codes are not validated." A "validation database" is comprised of a number of validation outcomes resulting from exercising the CFD model for a particular application. For example, a CFD model could be used to compute data which are validated with experimental data for a particular inlet across a range of Mach numbers (subsonic to transonic to supersonic) or angles of attack, etc., thereby forming the elements of a validation database. The validation database provides evidence that a CFD model has attained an acceptable degree of accuracy within the parameter domain, e.g., inlet shape, Mach range, etc., of the database. It does not, however, explicitly provide evidence regarding the accuracy of the CFD model when used outside of that domain.

Calibration processes focus on improving the agreement of computed results between CFD and test. Here the concept of agreement commonly entails a qualitative judgment on the difference between quantitative results. Elements of the CFD modeling are adjusted to reduce the difference.

On the other hand, validation processes focus on demonstrating a quantifiable estimation of differences between the CFD and test results to ascertain if the CFD results are sufficiently accurate for the intended purpose. The CFD results, and by inference the CFD model, are considered validated when results are shown to estimate the measured data within predefined accuracy requirements (referred to here as acceptance intervals) within the domain. The processes discussed apply to both calibration and validation of CFD results.

When a CFD model is used to produce flow data outside the validated parameter domain, the resulting data are referred to as a “*prediction*.” Reference 2.2.6 defines prediction as “use of a computational model to foretell the state of a physical system under conditions for which the computational model has not been validated.” The validation database provides no direct information regarding the accuracy of a prediction. However, when insight provided by the validation database is combined with understanding of the flow gained through previous experiments and flow physics, then *inferences* regarding the confidence in the predicted CFD results may be made. Small changes in the parameters used in the CFD model support strong inferences, while large changes in the parameters or complexity of the model weaken the strength of the inferences.

It is recognized that circumstances, e.g., related to schedule or resources, etc., may dictate that CFD be used to predict recovery and/or dynamic (peak) distortion of inlet systems for which no relevant test data exist. Calibration/validation of a CFD model for the intended use would not be possible in these circumstances. It should be recognized that the program is assuming a higher level of risk due to the lack of validation. Uncertainty associated with predictions using the chosen CFD model would be based on relevant demonstrated uses of the model and viability of the physics predicted in the flowfield. When CFD is used for predictions, the details of the CFD model, the range of previous validations, and the complexity of the inlet geometry and the air-vehicle flow field must be understood by all parties involved.

With this background and an eye to the future, this document provides processes to assist in the validation of CFD solutions for dynamic total-pressure distortion.

4. OVERVIEW OF VALIDATION PROCESSES

This section outlines recommended procedures to be followed by the CFD practitioner when generating dynamic-distortion data that are intended to be directly comparable to experimental results. It is a starting point for the mutual understanding of such processes between experimental and computational personnel. Since most experimental dynamic-distortion data are obtained from wind-tunnel tests, the experimental procedures will focus on those rather than flight tests. However, it has been found that when the recommended testing practices of ARP1420 are followed, the processes presented for wind-tunnel data are largely applicable to flight-test data after due consideration of scaling criteria for aerodynamic similarity parameters, data filtering, sample rates, and recording durations. It should be recognized that CFD-based flight data should be independently validated using flight-test data.

The procedures used to acquire dynamic total-pressure data and identify the peaks of dynamic distortion from that data are well established by inlet/engine development and test organizations. As outlined in Figure 3, the major steps lead from the high-response pressures through a series of data processing steps to a result consisting of the set of total pressures associated with the maximum value (peak) of computed distortion descriptors. Further details within the steps are discussed in Section 5.

The process contains two validation sequences, both of which are discussed in this document. The first sequence focuses on validation of the CFD-based dynamic total-pressure data as illustrated in the upper portion of Figure 3. For example, descriptive statistics, e.g., mean, variance, probability density functions (PDF), etc., are captured in this sequence. This provides inlet designers with a validated CFD database and model for use during development of the inlet. For validation of the CFD-based dynamic total-pressure data, an approach for estimating the needed sample size may be found in References 2.2.2 and 2.2.9. The size must be suitably large to reach a specified accuracy and provide statistical confidence (as indicated by α and β^3) and unbiased sample statistics. However, the size is significantly smaller than needed for validation of the CFD-based peak distortion data. For example, in a typical case, to validate the CFD-based total-pressure data would require a sample size of about 4000 observations, whereas the sample size for capturing the peak distortion is about 120000 observations.

³ Beta, β , is related to statistical power ($= 1 - \beta$), which is the probability that a statistical test will detect specified differences, e.g., in sample means, when they exist.