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Physical Modeling Techniques for Jet Engine Test Cell Aerodynamics

RATIONALE

While the concepts and techniques embodied within this document are valid, the technology is evolving slowly or not at all due to the shift in focus to computer based Computational Fluid Dynamics (CFD) simulations. As such, the decision has been made to stabilize this document. The reader is encouraged to evaluate both technologies as often physical scale modeling combined with data from actual full scale facilities can still be relevant to “ground” or validate the approach used in the CFD modeling.

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FOREWORD

One of the strongest motives for developing the scale modeling techniques to allow investigation of engine test cell aerodynamics as described in this work was the generally poor understanding of the aerodynamics associated with the ground level testing of turbofan and turbojet engines within enclosed testing facilities. In those instances where the understanding was not so poor, there sometimes remained a lack of appreciation for the fundamental importance of the aerodynamics of the engine testing environment. It is known that such a poor understanding or a lack of appreciation for the importance of the aerodynamics of the testing environment can and does lead to disastrous consequences. With proper attention to scale modeling techniques, the aerodynamics of a jet engine test facility can readily be investigated and documented. Modifications to a test cell based on scale model test results can lead to a stable and reliable full-scale operating environment for the testing of aircraft engines indoors. A much improved understanding and heightened awareness of the fundamental importance of the aerodynamics of the engine testing environment have resulted in significantly improved engine test facilities now in use world-wide.

ABSTRACT

Research studies focusing on jet engine test cell aerodynamics, acoustics, and cell flow characteristics as affecting engine performance can be conducted with scale models for a variety of test cells. Such studies require the simulation of a number of jet engines in rather accurate detail, both as to geometry and as to flow characteristics. It has been demonstrated that simulators of low-bypass afterburning turbojets, high-bypass turbofans, turboshaft engines (without propellers), and unducted fan engines can be designed, fabricated, and successfully operated using either high-pressure air ejector systems or turbine driven systems for the motive power. Specific components of a test cell such as inlets or exhaust sections alone may be tested independently by employing a vacuum source and bellmouth to simulate engine inlet flow or compressed air and scaled nozzle to simulate engine exhaust flow. The peculiar problems associated with scale model testing and engine simulators and the methods which can be used to attack these problems are described.

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1. SCOPE

This SAE Aerospace Information Report (AIR) has been written for individuals associated with ground level testing of turbofan and turbojet engines and particularly for those who might be interested in investigating the performance characteristics of a new test cell design or of proposed modifications to an existing test cell by means of a scale model test.

1.1 Purpose

The purpose of this information report is two-fold:

1.1.1 Provision of Guidelines

One of the primary purposes of this report is to provide guidelines for performing a scale model test of new configurations of and/or proposed modifications to a ground level enclosed test facility for turbofan and turbojet engine applications, i.e., a jet engine test cell.

1.1.2 Discussion of Considerations

Another important purpose is to address the major considerations when performing such a model test in the two main areas of the engine test cell model and the simulation of the engine. Requirements for the scale model test cell hardware and the associated instrumentation are presented and discussed. The requirements and considerations for the simulation of the engine are given, along with some of the special considerations which should be made when air ejector systems are the motive power for the simulator.

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

The following is a list of some applicable references and documents used in the preparation of this report:

- 2.1.1 Ashwood, P. F., and Mitchell, J. J.: "The Uniform Engine Test Programme", AGARD Advisory Report No. 248 (AGARD-AR-248), Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, Neuilly Sur Seine, France.
- 2.1.2 Freuler, R. J., and Dickman, R. A.: "Current Techniques for Jet Engine Test Cell Modeling", AIAA Paper No. 82-1272, Paper presented to the AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982.
- 2.1.3 Freuler, R. J.: "An Investigation of Jet Engine Test Cell Aerodynamics by Means of Scale Model Test Studies with Comparisons to Full-Scale Test Results", Ph.D. Dissertation, The Ohio State University, Columbus, Ohio, December 1991.
- 2.1.4 Karamanlis, A. I., Sokhey, J. S., Dunn, T. C., and Bellomy, D. C.: "Theoretical and Experimental Investigation of Test Cell Aerodynamics for Turbofan Applications", AIAA Paper No. 86-1732, AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference, Huntsville, Alabama, June 16-18, 1986.

- 2.1.5 Lee, J. D., and Freuler, R. J.: "Engine Simulator Techniques for Scaled Test Cell Studies", AIAA Paper No. 85-1282, Paper presented to the AIAA/SAE/ASME/ASME 21st Joint Propulsion Conference, Monterey, California, July 1985.
- 2.1.6 MacLeod, J. D.: "A Derivation of Gross Thrust for a Sea-Level Jet Engine Test Cell", Division of Mechanical Engineering Report No. DM-009, National Research Council Canada, Ottawa, Ontario.
- 2.1.7 SAE International Aerospace Information Report, "Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cells," SAE Standard AIR4869, Reaf. Sept. 2015.
- 2.1.8 Karamanlis, A. I., Freuler, R. J., Lee, J. D., Hoelmer, W., and Bellomy, D. C.: "A Universal Turboshaft Engine Test Cell - Design Considerations and Model Test Results", AIAA Paper No. 85-0382, Paper presented to the AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, January 1985.
- 2.1.9 Dickman, R. A., Hoelmer, W., Freuler, R. J., and Hehmann, H. W.: "A Solution for Aero-Acoustic Induced Vibrations Originating in a Turbofan Engine Test Cell", AIAA Paper No. 84-0594, Paper presented to the AIAA 13th Aerodynamic Testing Conference, San Diego, California, AIAA Conference Proceedings CP841, March 1984, pp. 99-108.
- 2.1.10 Kromer-Oehler, S. L. and Dietrich, D. A.: "Computational Analysis of the Flow Field in an Engine Test Cell", AIAA Paper No. 84-0285, paper presented to the AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984.
- 2.1.11 Barton, J. M.: "The Role of Computational Fluid Dynamics in Aeropropulsion Ground Testing", Journal of Aircraft, Vol. 10, October 1984, pp. 745-750.
- 2.1.12 Freuler, R. J. and Montgomery, K. A.: "Allison Gas Turbine Division Model AG9130/DDG-51 Ship Service Gas Turbine Generator Air Intakes Scale Model Test Report", Allison Gas Turbine Division Report No. EDR 14737, Allison Gas Turbine Division, Indianapolis, Indiana.
- 2.1.13 Smith, T. E.: "LM1600 Bravo-Romeo Project - Wind Tunnel Test to Determine Engine Inlet Flow Quality", General Electric Technical Memorandum, TM No. 90-460, GE Aircraft Engines, Cincinnati, Ohio.
- 2.1.14 Eckert, D., van Ditschuijzen, J. C. A., Munniksma, B., and Burgsmuller, W.: "Low Speed Twin Engine Simulation on a Large Scale Transport Aircraft Model in the DNW", ICAS Paper No. 84-2.10.4, Proceedings of the 14th Congress of the International Council of the Aeronautical Sciences, Vol. 2, Toulouse, France, September 10-14, 1984.
- 2.1.15 Harris, A. E. and Paliwal, K. C.: "Civil Turbofan Propulsion System Integration Studies Using Powered Testing Techniques at ARA, Bedford", AIAA paper No. 84-0593, Proceedings of the AIAA 13th Aerodynamic Testing Conference, San Diego, California, AIAA Conference Proceedings CP841, March 1984, pp. 74-98.
- 2.1.16 Wagenknecht, C. D., Hoff, G. E., and Norbut, T. J.: "Performance Calibration Results for a Compact Multimission Aircraft Propulsion Simulator", AIAA Paper No. 82-0254, Paper presented to the AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, January 11-14, 1982.

- 2.1.17 Smith, G. D., Matz, R. J., and Bauer, R. C.: "Analytical and Experimental Investigation of Ejector- Powered Engine Simulators for Wind Tunnel Models", AEDC-TR-76-128, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee.
- 2.1.18 Hoelmer, W. and Freuler, R. J.: "Lufthansa German Airlines, Frankfurt Test Cell Aero Evaluation, Scale Model Test Program", International Engine Support Operations Memorandum Report, GE Aircraft Engines, Cincinnati, Ohio.
- 2.1.19 Minardi, J. E. and Von Ohain, H. P.: "Thrust Augmentation Study of High Performance Ejectors", AFWAL-TR-83-3087, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.
- 2.1.20 Lau, J. C.: "Effects of Exit Mach Number and Temperature on Mean-Flow and Turbulence Characteristics in Round Jets", Journal of Fluid Mechanics, Vol. 105, 1981, pp. 193-218.
- 2.1.21 Quinn, B.: "Ejector Performance at High Temperatures and Pressures", Journal of Aircraft, Vol. 13, December 1976, pp. 948-954.
- 2.1.22 SAE International Aerospace Information Report, "Inlet Airflow Ramps for Gas Turbine Engine Test Cells," SAE Standard AIR5306, Stab. Dec. 2013.
- 2.1.23 SAE International Aerospace Information Report, "Design Considerations for Enclosed Turboshift Engine Test Cells," SAE Standard AIR4989, Rev. Sept. 2013.

2.2 Symbols and Abbreviations

The following parameters, abbreviations, and subscript notations are used in this report:

2.2.1 Parameters

Parameter units throughout this report are dual dimensioned primarily in SI Units with US Customary Units in brackets.

A	cross-sectional area, square centimeter [square inches] or square meters [square feet]
Cd	flow coefficient, non-dimensional
g	gravitational constant, meters per second per second [feet per second per second]
$\dot{m}$	mass flow rate, kilograms per second [slugs per second]
M	Mach number, non-dimensional
p	pressure, Pascal [pounds per square inch, pounds per square foot, or inches of water]
R	gas constant, joules per kilogram kelvin [square feet per square seconds-degrees Rankine]
Re	Reynolds number, non-dimensional
T	temperature, degrees kelvin [degrees Rankine]
V	velocity, meters per second [feet per second]
W	airflow rate, kilograms per second [pounds (mass) per second]
α	cell bypass ratio, non-dimensional
γ	ratio of specific heats, non-dimensional
ρ	density, kilograms per cubic meter [slugs per cubic foot]

2.2.2 Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
AGARD	Advisory Group for Aerospace Research and Development
BM	bellmouth
EPS	ejector-powered simulator
FC	front cell
GE	GE Aircraft Engines
PVC	polyvinyl chloride
rpm	revolutions per minute
SAE	Society of Automotive Engineers
TPS	turbine-powered simulator
UETP	Uniform Engine Test Programme

2.2.3 Subscripts

amb	ambient condition
avg	average
BM	bellmouth
Dist	distortion
e	nozzle exhaust plane
FC	front cell
flow	flow function
max	maximum
min	minimum
s	static
t	total
x	station where $p = p_{\infty}$
∞	local ambient

3. TECHNICAL BACKGROUND

Gas turbine engine manufacturers and their customers have the requirement to test engines for the purposes of determining performance, verifying repairs, and insuring proper functioning of all engine systems prior to the installation of an engine and its use on-wing. Inherent in such testing is the need to determine engine performance in absolute terms with a high degree of accuracy in a reliable, repeatable testing environment. An important, central issue to gas turbine engine testing is the conflict between the need for accuracy of performance measurements and the need for a reliable, repeatable test environment. An outdoor "free-air" test environment represents the best possible "ideal" condition in terms of thrust measurement. When an engine is tested on an outdoor stand under no-wind conditions, it draws only the air required to satisfy the thermodynamic cycle with the result that all the measured thrust force is considered to be the "true" thrust of the engine (see 2.1.6).

Thus, it would seem that the proper approach for all ground-level testing of engines might be to use outdoor, "free-air" test stands. Since testing at an outdoor stand is so strongly dependent on the weather and wind conditions, it should be obvious that such an approach is not practical when faced with the requirement of a reliable and repeatable test environment. Additionally, of course, the use of outdoor facilities can result in objectional noise pollution. As a consequence, they are likely to be located in more remote, less accessible areas. Accordingly, it is standard practice to conduct most jet engine testing indoors in specialized test facilities, and to correct for the various effects that alter the performance measurements of an engine when it is operated inside a building. In order to determine the actual performance characteristics of an engine when tested indoors, the interaction between the engine and the test cell environment must be understood and evaluated. This has a direct analogy to determining wind tunnel interference effects which are required for a proper understanding of aerodynamic performance characteristics of models tested in wind tunnels.

To underscore the importance of understanding performance measurements from engine test facilities, one of the most extensive experimental and analytical programs ever sponsored by the Advisory Group for Aerospace Research and Development (AGARD) is cited (see 2.1.1). This program, "The Uniform Engine Test Programme" or UETP, was proposed by the Propulsion and Energetics Panel and approved by AGARD in 1980. The objectives of the program were:

- a. "To provide a basis for upgrading the standards of turbine engine testing within AGARD countries by comparing test procedures, instrumentation techniques and data reduction methods, thereby increasing confidence in performance data obtained from engine test facilities, and
- b. To compare the performance of an engine measured in ground-level facilities and in altitude facilities at the same nondimensional conditions and establish the reasons for any differences."

The UETP involved testing two turbojet engines in five countries using four altitude test facilities and four ground-level test beds. The testing program began in 1981 and extended over a period of approximately seven years. The program has had an historic importance in that for the first time it has made possible direct comparison of engine performance as measured in a closely controlled test program over a range of altitudes and flight speeds, in different facilities, and using different methods of data acquisition and reduction according to 2.1.2. One of the key contributions of the UETP to the participating countries was the derivation and implementation of a standard methodology for objective assessment of the quality of measured engine performance in the various test facilities. Each participant in the UETP found anomalies in his/her test facility and evaluation techniques which have caused an internal re-evaluation. Problems varied in degree, but in some cases the problem would not have been discovered without the ability to compare to other facilities (see 2.1.1). It should come as no surprise that two of the performance parameters most closely studied were engine thrust and specific fuel consumption.

The correction to measured thrust for the so called "test cell effect" is variously known as the test cell correlation factor, cell correction factor, facility modifier, or simply, cell factor. The cell factor results primarily from the momentum of the air approaching the engine acting as a headwind, which reduces indicated engine thrust. It is also modified by pressure forces acting on engine surfaces which differ from those that would be felt in the outdoor environment. In practice, a number of the measured engine performance factors besides thrust must be adjusted for the "test cell effect", and so a set of modifiers or factors must be determined. In spite of the need to accurately determine the cell factor, testing indoors has the significant advantages of being able to operate with limited restrictions imposed by unfavorable weather conditions, of offering the opportunity for noise control and abatement, and of allowing a wider choice of locations. But even before the cell correlation factors can be determined, the first and most important step is to provide the proper indoor testing environment.