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Test Cell Analytical Thrust Correction

RATIONALE

For accurate, indoor ground-level testing of jet engines, the influence of the test cell on the thrust produced by the engine must be established. The "true" gross thrust may be derived from the measured scale force, if the aerodynamic conditions inside the test cell are known. The "test cell effect" may also be quantified using correlation factors determined from comparison of test data taken from indoor facilities, and reference outdoor, or "free-air" test stands.

In this report, the influence of the test cell on engine performance is described. The forces measured in a particular indoor test cell are derived. The results show that if all the aerodynamic forces have been accounted for, the corrected thrust in an indoor cell is the "true" gross thrust. As this paper is a derivation from first principles, there will never be a requirement to revise this document.

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1. SCOPE

This document describes a method to correct engine thrust, measured in an indoor test cell, for the aerodynamic effects caused by the secondary airflow induced in the test cell by the engine operating in an enclosed environment in close proximity to an exhaust duct. While it is not recommended to be used to replace test cell correlation, it does provide a means to verify an existing thrust correlation factor.

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 724-776-4970 (outside USA), www.sae.org.

ARP741B Turbofan and Turbojet Gas Turbine Engine Test Cell Correlation

ARP755B Aircraft Propulsion System Performance Station Designation and Nomenclature

2.1.2 Other Publications

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2.2 List of Symbols

2.2.1 General

A	Area
α	Bypass ratio
C	Coefficient
dhF	Deviation from standard day enthalpy
F	Thrust
FAP	Thrust parameter (F/AP)
FAR	Fuel-air ratio
γ	Specific heat ratio
H	Total enthalpy
h	Specific enthalpy
LHV	Lower heating value
LPC	Low - pressure compressor
LPT	Low - pressure turbine
η	Efficiency
P	Static pressure

ρ	Density
q	Dynamic pressure
Q	Heat rate
T	Temperature
V	velocity
v	Volume
W	Airflow
WARO	water/air ratio
WF	Fuel flow
WORK	Work rate

2.2.2 Subscripts

amb	Ambient
bt	Boattail
c	Combustion
d	Drag
e	Nozzle exit
f	Friction
fw	Wall friction
g	Gross
i	Incremental
im	Inlet momentum
imd	Intrinsic momentum drag
in	Intake
m	Measured
out	Outlet
pbt	Boattail, projected
ref	Reference

stack	Exhaust stack
t	Time
tf	Thrust frame
tot	Total
w	Wall, surface
wet	Wetted
x	Axial direction
0	Inlet reference plane in test section
∞	Ambient free stream

3. INTRODUCTION

The requirement to quote engine performance in absolute terms has become increasingly more important in the last decade. With new higher performance engines and the reliance on accurate absolute engine performance data needed to estimate the capabilities of new aircraft designs, the future requirements of quality engine test cell data will be increasingly stringent.

Accurate, controlled testing of high-technology gas turbine engines requires installations where engines may be operated throughout their entire thrust range under approximately sea-level-static conditions. When a jet engine is run in an indoor test cell, its performance is altered because of aerodynamic interference between the engine and the cell. To establish the "true" performance of the engine, the interaction between the engine and the test cell environment must be evaluated. This is analogous to the installation effects experienced in wind tunnel testing. There are several factors that contribute to the "test cell effect." The major factors are test cell geometry and the size of the engine relative to the cell. The minor factors include test cell wall friction losses and exhaust back pressure.

The reasons for analyzing the effects of test cell environment on engine performance are important. Engines of similar types are tested in a wide variety of test facilities, ranging from old reciprocating engine test cells converted to jet cells, to modern cells specifically designed for turbofans. The types of testing performed in each of these cells may vary from a basic function-and-leak check to sophisticated research tests. No matter how simple or complex the type of testing may be, the common factor is the need to compare data recorded from one facility to another or to declare the performance relative to a known reference standard. Depending upon the design and operating conditions of the test facility, the magnitude of the "test cell effect," and hence the correlation factor used to relate one cell to another, could vary greatly.

There are many factors in test cell configuration and design, some of which may not be controllable or well understood that can effect test cell correlation. While specific design characteristics vary from one facility to another, the basic test cell consists of an air intake, a test section, and an exhaust outlet. In most cases, both the intake and exhaust sections are acoustically treated to reduce the noise pollution in the surrounding vicinity. All three sections of the test cell have a strong influence on the magnitude of the "test cell effect." Without fully understanding the effect that the test cell has on the performance of the engine, it is impossible to accurately measure the difference between the performance of an engine tested inside two different test cells, or to an engine installed in an aircraft.

The performance results from a test cell will only be relative to some unknown datum unless a correlation between that test cell and an outdoor, "free-air" test stand has been carried out. In gas turbine engine testing, the outdoor "free-air" test represents the ideal condition in terms of thrust measurement. When an engine is tested on an outdoor stand during no-wind conditions, the engine only draws the air that it requires to satisfy the thermodynamic cycle. For this reason, all the scale force measured is considered to be the "true" thrust.

The ideal solution would be to do all ground level engine testing on outdoor stands. However, this is obviously not practical, especially in harsh climates. With the proper correlation factors known, any test facility should be able to quote absolute performance results.

Following the various studies of test cell effects, it appears that many of the engine test cells being used today are operating unaware of what effects the test cell environment is having on engine performance. Therefore, it is intended that this report will begin to consolidate and rationalize the existing knowledge of test cell and engine interactions, and consequently improve the quality of engine testing in general.

The main purpose of this report is to identify the contributing components of the "test cell effect," and attempt to quantify them using variables readily measured during an engine test. Having identified these components, correlation of test cells could then be more accurate. This approach would particularly apply to correlations used for engine manufacturer's development and production test cells, engine and airframe test facilities, or military depot and overhaul contractor sites. Test cell designers would also benefit from this information by establishing design criteria for future test cells, thus controlling the "test cell effect."

4. CELL DESIGN CONSIDERATIONS

There are three types of gas turbine engine test facilities: altitude chambers, ground level indoor cells, and "free-air" test stands. For the purposes of this study, only the ground level, enclosed facility will be considered. A typical layout of a general test cell is given in Figure 1. The basic test cell is made up of three components: the air intake, the test section, and the exhaust outlet. A description of some of the test cell design criteria is presented here, so that one might more fully understand the complex interaction between the engine and the test cell. Each of the three major components of the cell will be discussed separately.

4.1 Air Intake

The intake of the test cell may be either horizontal or vertical with turning vanes. The main design criteria for the intake are to attenuate the noise produced by the engine, while providing a fully uniform, low-turbulence flow field to the engine face, with minimal pressure loss of the incoming airflow. The airflow path should be relatively unrestricted and of sufficient size to keep the air velocity in the cell to a minimum, thus reducing the static pressure depression. It is desirable to keep the cell ambient static pressure depression to about 1 in (2.54 cm) of water to minimize the air pressure and ram ratio correction factors, and to reduce undue stresses on the building caused by the pressure differential (SAE 1976).

Engines operating within a test cell can encounter temperature and pressure distortions in the engine inlet, which introduce increased uncertainty about performance measurements, since most engine parameters are referenced to the inlet conditions at the compressor face (Karamanlis et al. 1985). These distortions are generally attributed to the aerodynamic design of the cell and are more likely to occur when one cell is used to test several engines with different airflow requirements and installation configurations. Problems arising from these distortions can be as minor as unsteady engine speed or thrust, or in the worst case, a complete stall which could result in serious engine damage (Lee and Freuler 1985). Poor cell inlet design is a major contributor to the formation of flow distortion and vortex generation. Inlet type, turning vane geometry, screen density, and silencer baffles all influence the flow uniformity. The inlet should also be designed such that test cell performance is independent of outside wind direction and magnitude.

General Electric, for example, in their design criteria for cell inlets, states that an acceptable cell shall have a front cell velocity distortion of only 20%, with no vortices entering the engine bellmouth, and a minimal effect on the velocity distortion, when influenced by a 32 km/h crosswind (Karamanlis et al. 1986).

4.2 Test Section

After the incoming air passes through the inlet, it enters the test section where the engine is mounted on a thrust cradle. While inlet and outlet configurations may vary from one facility to another, test sections tend to be similar in layout. An important factor in test section design is the geometric ratio of engine diameter to the cross-sectional area of the cell. Another significant design consideration is the bypass ratio, which is defined as the ratio of the secondary air flowing past the engine to the airflow entering the engine inlet. Both the bypass ratio and the area ratio have a direct influence on the velocity of the air bypassing the engine, which should preferably be less than 9.8 m/s (SAE 1976). To meet this requirement, the maximum engine size for a given test section may be approximated by

$$W_e = 12 \frac{A_{\text{cell}}}{\alpha + 1}$$

where:

W_e = maximum engine airflow (kg/s)

A_{cell} = test section flow area (m²)

α = bypass ratio

High bypass air velocities cause a reduction in static pressure along the engine length, resulting in forces that would not occur in open-air testing. These pressures acting on the engine will alter the measured thrust by producing axial buoyancy forces. The major effect of these buoyancy forces is generally near the exhaust end of the engine where the secondary flow velocities are high. If the flow velocity in the test section is significant, tailpipe ambient pressure will be reduced relative to the engine inlet pressure. The result is equivalent to the engine operating with an apparent forward velocity, and at a slightly higher altitude. The use of a high loss protective screen in front of the engine may lower the inlet pressure to the engine even further.

Flow along the test section wall experiences a rapid acceleration as it approaches the engine bellmouth, since the flow captured by the engine has a cross-sectional area larger than the engine itself. Boundary layer analysis (Kromer and Dietrich 1985) indicates that flow along the wall separates for all cell bypass ratios. The separation location moves downstream as the bypass ratio increases. For high bypass ratios, the separation point moves downstream of the bellmouth entry plane, which will prevent vortex ingestion. For low bypass ratios, the flow separation point moves upstream of the bellmouth inlet, which may lead to vortex formation. Keeping the separation point at or behind the bellmouth inlet should reduce vortex formation (Kromer and Dietrich 1985). An approach to eliminate vortex formation is to reduce the diffusion along the test section walls, by reducing the cross-sectional area of the cell in the vicinity of the bellmouth inlet. However, varying the cross-sectional area of the cell will create additional pressure forces, which then must be properly accounted for in calculating gross thrust.

A secondary design consideration for test sections is streamlining. Any projections into the airflow of the cell, such as heating ducts, piping, or lighting fixtures, may induce the formation of vortices, which could be ingested into the engine. Even the thrust stand to which the engine is attached should be carefully designed. To reduce the pressure forces generated by the air flowing past the engine, the stand should be aerodynamically streamlined.

4.3 Exhaust Outlet

Probably the greatest impact on engine performance is the design of the exhaust outlet. The exhaust outlet not only controls the amount of secondary airflow in the cell, but it also controls the back pressure on the engine, the sound absorption, and the production of exhaust pollution. Most modern engine testing facilities use an augmentor tube to capture the engine exhaust gas and induce secondary airflow through the cell. The exhaust is directed into the augmentor tube and then expelled into the atmosphere. The augmentor tube acts in combination with the engine exhaust momentum to form an ejector, which entrains cool, secondary air from the test cell. In the past, augmentor design was basically an art and test facility people had only quantified some of the parameters concerning ejector performance (Sappand and Netzer 1978).

The secondary or bypass flow is important for cooling the exterior of the turbine casing and the exhaust duct of the engine, as well as the exhaust silencer and the augmentor tube itself. It is preferable to use an augmentor tube that has a collector which can be moved relative to the engine exhaust plane, and a variety of insert sizes to modify the flow area. This type of design allows easier control over the airflow pumping requirements, noise, and local static pressure at the jet nozzle exit plane. More importantly, the quantity of secondary air entrained is crucial for proper engine testing (Hayes 1975). Too little secondary air allows recirculation of exhaust gases within the cell, resulting in overheating of the engine components and the augmentor tube. Too much secondary air causes excessive static pressure gradients between the engine inlet and exhaust planes, which require large corrections to the measured thrust. However, sufficient secondary air must be entrained to lower the kinetic energy of the exhaust, to allow the silencing equipment to perform properly. Turbofan engines, for example, tend to overpump the system and the augmentor tube must be modified to restrict the amount of entrained air (Sapp and Netzer 1978).

The major design elements of an augmentor tube include the nozzle/augmentor diameter ratio, the inlet configuration, the engine airflow, the spacing between the engine nozzle and augmentor tube, and the engine exhaust temperature. Each of the parameters will have an effect on the cell bypass ratio, the total cell airflow, and the pressure, temperature, and velocity profiles in the augmentor tube.

The collector to engine nozzle diameter ratio is a very important parameter in the augmentor design. The bypass ratio decreases with decreasing diameter ratio because of the reduced secondary flow area (Hastings 1983). As the diameter ratio increases, the entrance losses become less important because the secondary air enters the augmentor tube in a more axial direction. A converging-diverging engine nozzle will reduce the bypass ratio because of the increased secondary flow blockage from the diverging nozzle flow, and because of the decreased diameter ratio from a modulating nozzle.

There are several types of augmentor tube inlets in use today. The bellmouth and conical inlets are the most commonly used designs, because they are the most efficient at pumping air. Straight-edged inlets result in increased entrance losses, which reduces the flow capacity. Reverse conical or flat plate designs have very high loss factors, which reduce the cell bypass ratio and may result in damage to the augmentor tube because of recirculation of hot exhaust gases inside the tube itself (Sapp and Netzer 1978).

The airflow of the engine being tested in the cell has a direct impact on the operation of the augmentor tube. For a fixed exhaust nozzle, as the engine airflow increases from idle to maximum power, the secondary airflow increases, but the cell bypass ratio decreases. This relationship between engine airflow and bypass ratio has been found to apply to the full spectrum of engine sizes. Large engine installations usually operate with a cell bypass ratio between 1.0 and 2.0, although some operate below 1.0. For small engines, normal bypass ratios can be greater than 5.0. The operation of a large engine in a test cell at low bypass ratios can amplify or introduce adverse flow effects that can occur during engine testing. The bypass ratio influences the location of the engine airflow stagnation point in the bellmouth. Decreasing the bypass flow moves the stagnation point upstream, while increasing the bypass flow moves it downstream towards the engine compressor face. The location of this stagnation point has a strong influence on the compressor blade tip circumferential and radial distortion, which may affect compressor performance (Freuler and Dickman 1982). High-bypass turbofan engines are more susceptible to inlet distortion and vortex ingestion than low-bypass engines, because of their increased inlet flow area.

The spacing between the engine nozzle and augmentor tube has less influence on the secondary airflow. The bypass ratio increases slightly with spacing because of reduced blockage of the nozzle and then decreases because of increased flow blockage of the spreading exhaust plume (Sapp and Netzer 1978). More importantly, the spacing affects the static pressure field at the nozzle exit, which ideally should be the same as the static pressure field around the engine. Increasing the spacing causes an increase in the noise produced within the cell, because of the larger shear layer between the jet exhaust stream and the low-velocity secondary air.

The secondary cell bypass flow is also a function of the engine exhaust temperature. The cell bypass ratio varies approximately as the square root of the ratio of the exhaust total temperature to the engine inlet total temperature (Hastings 1983). Military engines, because of their inherently higher exhaust plume temperatures, induce higher bypass ratios.

The interaction between the high-temperature exhaust plume and the secondary cooling air also influences both the noise and exhaust pollutants emitted from the test cell. For non-afterburning engines, the temperature of the exhaust gases is sufficiently low that the chemical reactions are kinetically inactive and the secondary air merely dilutes the existing pollutants. For afterburning engines, the exhaust temperatures are high enough to allow chemical reactions to occur outside the engine and the secondary flow will react with the exhaust, thus modifying the type and concentration of the pollutants emitted from the test cell.

4.4 Future Trends

Model testing is a useful tool to study cell and engine flow interactions, to develop new test cell designs, or to modify existing cells. For more than a decade there has been a significant increase in the size, thrust, and airflow of gas turbine engines. In contrast, there has not been any significant change in most engine test cells, which were generally designed and constructed for much smaller airflow engines.

With the future demand for higher thrust-to-weight ratios, the next generation of engines will consume more air and produce higher thrust. The current development of ultra high bypass and propfan engines indicates that the trend is towards more airflow. Existing ground level test facilities may experience difficulty in accurately measuring the performance of these new engines because of the increased aerodynamic interference of the test cell.

5. ANALYTICAL THRUST CALCULATIONS

To accurately calculate correlation factors to account for the "test cell effect," it is essential to completely describe the measurement of thrust. For gas turbines, thrust is defined as the momentum increase of the air passing through the engine. The term gross thrust designates the force that can be attributed to the engine under static conditions, i.e., no forward motion or ram effects. The engine is responsible for accelerating the air from rest to the prevailing inlet velocity, and any drag forces are properly credited as thrust corrections to static conditions. Most of the existing literature on thrust measurement focuses on in-flight thrust derivation; however, there is enough information available to describe the components of thrust in an enclosed ground level test cell. A summary of this information from these articles follows.

5.1 Literature Survey

From the existing literature, four representative samples of information regarding the definitions of thrust components and correction factors for external drag forces have been reviewed. Ashwood (1984) gives the definitions of gross thrust and its components. The standard gross thrust is the sum of the intrinsic thrust and the intrinsic momentum drag. The standard gross thrust is the stream force at the exit plane of the nozzle and is mathematically defined as

$$F_g = W_e V_e + A_e (P_e - P_\infty) \quad (\text{Eq. 1})$$

where:

W_e = nozzle exit airflow

V_e = nozzle exit velocity

A_e = nozzle exit area

P_e = nozzle exit static pressure

P_∞ = ambient free stream static pressure

The intrinsic momentum drag is calculated by

$$F_{imd} = W_0 V_0 + A_0 (P_0 - P_\infty) \quad (\text{Eq. 2})$$