Calculation of aerodynamic drag forces in an engine test cell

Sivapragasam¹, Kannan¹
¹ RMD, MSRSAS, ² Team Leader, Engine Performance & Operability, Safran Aerospace India Limited, Bangalore

Abstract
The performance of an aero gas turbine is evaluated in an engine test cell. A test cell is defined as a wind tunnel with an engine mounted on a thrust frame, aiming to generate ideal environment conditions for accurate and steady engine performance testing. The turbojet and turbofan engines are very sensitive to test cell aerodynamic parameters. This paper describes the calculation of aerodynamic drag forces by direct measurement method.

Keywords: Gas turbine, test cell, aerodynamic drag forces, thrust correction

Nomenclature
m – engine inlet mass flow, kg/s
A – thrust frame frontal area, m²
A_{jet} – area of nozzle exit, m²
A_{jet} – area of nozzle inlet, m²
C_d – mean coefficient of drag of thrust frame
D_i – intake momentum drag, kN
D_n – nozzle drag, kN
D_f – thrust frame drag, kN
P – test cell static pressure, kPa
P_e – nozzle external static pressure, kPa
V_i – airflow approach velocity, m/s
V_{max} – maximum approach velocity, m/s
V_{min} – minimum approach velocity, m/s
V_t – entrained air velocity, m/s
Δp – pressure loading, kPa

1. Introduction
The gas turbine is the most amazing machine man has ever built. An aero gas turbine is certified for flight after rigorous tests, both on the ground and in flight. The performance evaluation of the aero engine is carried out with utmost care and integrity. The performance data should be reliable, accurate, repeatable and should guarantee safe operation of the engine under design and off-design operating conditions.

The engine is comprehensively tested in a sea-level test facility. A test cell can be considered as a wind tunnel inside which an engine is mounted on a thrust frame, aiming to generate ideal environment conditions for accurate and steady engine performance testing. In particular, the turbojet and turbofan engines are very sensitive to test cell aerodynamic parameters. The measured thrust of the engines may be less by 2% to 5% in comparison to its gross thrust. This is due to the aerodynamic drag forces caused by the airflow in the test cell. These drag forces are to be accurately estimated or measured and added to the observed engine thrust to obtain the gross thrust. The methods of calculating the aerodynamic drag forces by direct measurement are described in this paper.

2. Sea-Level Test Facility
Sea-level test facilities are of open or of fully enclosed type. The open test facility is less common, although they provide the best possible reference for measurements taken from enclosed and altitude test facilities. The open test facility is strongly influenced by prevailing ambient conditions and wind direction thus rendering it unusable during adverse weather conditions. Also due to the ever-increasing concern on noise pollution, open test facilities are not favoured.

The essential elements of a fully enclosed sea-level test facility are illustrated in Fig. 1. The engine on test is mounted on a test frame, which is installed in the test cell. Air is drawn inside the test cell through zigzag intake splitters. The air enters the engine through an aerodynamically designed intake flare called the bellmouth. The engine exhaust gases are ducted outside the test cell through a large silencer duct called the detuner.

3. Aerodynamic Drag Effects
When a gas turbine engine is operated in a test cell, its performance is altered because of the aerodynamic interactions between the engine and the cell. The primary problem is the determination of the gross thrust. The airflow induced through the test cell by the high velocity engine exhaust gases imposes a drag on the engine and the thrust stand. By adding the drag to the measured thrust, the gross thrust of the engine is obtained.

4. Momentum Balance Approach
The aerodynamic drag forces can be theoretically evaluated by a momentum balance across the detuner as described by Rudnitski [1]. By this approach, all the drag forces associated with the air velocity within the test cell can be evaluated.

5. Direct Measurement Approach
The direct measurement approach offers a quick and effective evaluation of the drag forces by means of a few additional measurements. The drag forces calculated by the momentum balance principle can be validated by this method.
6. Aerodynamic Forces
Aerodynamic drag forces arise from flow-induced forces within the test cell, and can be divided into three major components:
- Intake momentum drag
- Thrust frame drag
- Carcass drag

7. Intake Momentum Drag
The most significant of the aerodynamic drag forces is the intake momentum drag. This drag force is produced on the engine as a result of air being drawn into the test cell. The intake momentum drag is a function of the engine intake airflow and the approach airflow velocity in front of the engine. The approach velocity is significantly affected by the total test cell airflow and the test cell geometry. It is usual practice, to limit the approach velocity to 10 m/s as specified by Walsh & Fletcher [2].
The intake momentum drag is calculated by measuring the airflow approach velocity ahead of the engine intake using anemometers mounted on a cruciform. This cruciform is axially positioned about 2 to 3 bellmouth throat diameters upstream of the engine intake. The anemometers, usually 9 off are secured to the cruciform by fasteners, to prevent them from being ingested by the engine. One anemometer is installed on the engine centreline, and four others at a distance of 0.75 bellmouth throat diameters at 90° circumferential increments. The additional four anemometers are installed on the cruciform as illustrated in Fig. 2.
Intake Momentum Drag, \( D_i = m \cdot V_i / 1000 \text{ kN} \)
where, \( m \) = observed engine inlet mass flow, in kg/s
\( V_i \) = mean approach velocity, in m/s
\( V_i \) is calculated as the average of the 9 anemometer readings mounted on the cruciform.
The measurements taken from these anemometers are a good indication of the velocity profile ahead of the engine in the test cell. Inlet velocity distortion directly affects the engine stability/stall margin, thrust and airflow measurement.

8. Thrust Frame Drag
The total drag force on the moving part of the thrust frame is calculated from the local air velocity measurements or can be measured by pressure drops across those components of the frame which are exposed to the airflow.
The former method is particularly advantageous in that the anemometers directly measure the air velocity, instead of calculating them by the pressure difference across the frame components. The anemometers, usually 10 off are mounted at strategic locations on the moving part of the thrust frame.
The thrust frame drag can be directly calculated from the pressure loading exerted by the airflow on the frontal blockage areas of the members of the thrust frame. The frontal area of all the moving parts of the thrust frame exposed to the airflow is calculated either from drawings or can be actually measured. The drag coefficients associated with each chosen member are estimated from the cross-sectional shape of the member using the data shown in Fig. 3, extracted from Hoerner [4].
Pressure loading,
\[
\Delta p = P \left( 1 - \frac{1}{1 + (6.045 \times 10^{-6} \cdot V_i^2)} \right), \text{ kPa}
\]
...(2)
where, \( P \) = test cell static pressure, in kPa
\( V_t \) = mean entrained air velocity, in m/s
\( V_t \) is calculated as the average of the 10 anemometer readings mounted at various places on the thrust frame.
Thrust frame drag, \( D_f = \Delta p \cdot A \cdot C_d \), kN
where, \( \Delta p \) = pressure loading, in kPa
\( A \) = total thrust frame frontal area, in m²
\( C_d \) = coefficient of drag of mean frontal thrust frame geometric blockage area

Figure 3. Drag Coefficients for various cross-sections

The primary design criteria in the test frame design are ease of engine installation and removal. It should provide for maximum accessibility to engine during maintenance and inspection. For this purpose, working platforms are constructed around the engine. These platforms should in no way obstruct the airflow into the engine. They should not affect the static pressure field around the engine. A collapsible working platform is ideal, so that the platform can be collapsed to flush with the floor once the engine rigging is complete. But even in such cases, care should be taken to have no protrusions ahead of the engine bellmouth.

9. Nozzle Drag
The nozzle drag is caused due to the scrubbing of air over the engine carcass and the exhaust nozzle. Due to the close proximity of the exhaust nozzle to the detuner inlet, the secondary airflow accelerates past the nozzle and sets up a static pressure gradient along the external surface of the nozzle.

The nozzle drag can be calculated by measuring the mean static pressure depression that results from the accelerating secondary airflow as they flow over the exhaust nozzle. This ejector effect creates a suction force, which can be calculated. The static pressure on the nozzle is measured by 4 off tapings located circumferentially, as shown in Fig. 4. Nozzle drag, \( D_n = (A_{jui} - A_{jpe}) \cdot (P - P_e) \), kN
where, \( A_{jui} \) = area of the nozzle inlet, m²
\( A_{jpe} \) = area of the nozzle exit, m²
\( P \) = test cell static pressure, kPa
\( P_e \) = nozzle external static pressure, kPa
\( P_e \) is calculated as the average of the 4 external static pressure tapings.

The nozzle drag can be minimised by carefully positioning the detuner relative to the exhaust nozzle. The optimum axial gap is thrice the engine nozzle diameter. It is highly desirable that this gap is adjustable, as the detuner gap has a very strong influence on the measured thrust. The optimum detuner gap can be assessed during the test cell commissioning exercise.

Figure 4. Nozzle External Static Pressure Measurement

Thrust Correction

The overall thrust correction is the sum of these drag components. Since the engine is the prime mover responsible for accelerating the air from rest to the prevailing cell velocity, the drag must be credited to the engine as a thrust correction. In a well-designed facility, the intake momentum drag accounts for nearly 80% of the thrust correction. The drag components and the total drag are plotted in Fig. 5.

10. Conclusion
This paper has described the calculation of the aerodynamic drag forces in an engine test cell by the direct measurement method. The direct measurement method is a quick and effective means of evaluating the drag forces. These measurements directly indicate the quality of airflow in the test cell.
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Reference

