DERIVATION OF AERODYNAMIC THRUST CORRECTION FOR AN INDOOR GAS TURBINE ENGINE TEST FACILITY USING THE "FIRST PRINCIPLES" ANEMOMETER METHOD

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Abstract

This "first principles" methodology enables the direct "in situ" measurement and calculation of the wind tunnel drag effects acting upon the engine and it's support structure, that are necessary to derive the aerodynamic thrust correction for an indoor test facility, and thus, eliminate the need for outdoor "free field" testing.

1 Introduction and Background

An indoor gas turbine engine test facility is by design, a low speed wind tunnel. The wind tunnel effect is created by a secondary demand for ambient airflow as a result of the ejector pump action of the engine exhaust jet plume entering the test facility exhaust collector (detuner). This ejector can create a secondary demand for entrained/by-pass airflow that is up to five times greater than the initial airflow being demanded by the engine/intake. In this case, this would describe a test facility with an entrainment ratio of 5 to 1.

The creation of this wind tunnel effect is necessary to assist expelling all undesirable hot gasses from the test cell, to enable meaningful engine performance measurement and repeatability in a stable and consistent aerodynamic environment of non-turbulent ambient airflow. This will help eliminate any potential instability, hot gas re-ingestion or vortex formation. Also, exposed elements of test facility instrumentation/measurement systems can be cooled with ambient airflow to avoid overheating.

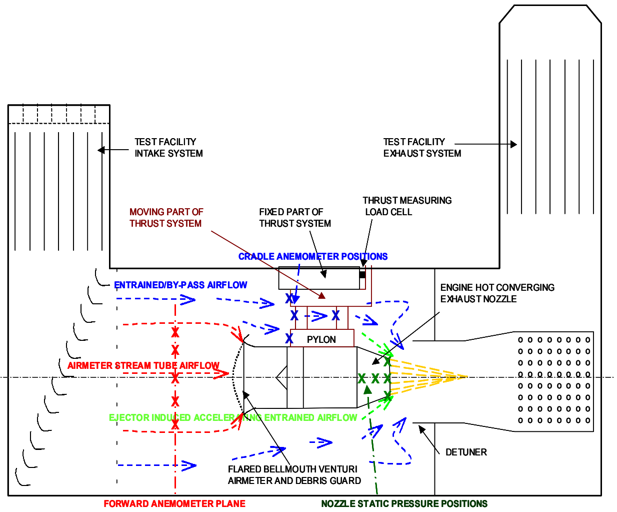
However, this wind tunnel effect creates a drag force acting upon the engine and its support structure, in an opposing direction to the test facility thrust measuring load cells. Therefore, it is necessary to account for this thrust drag debit (typically between 1-8%) with some form of calibration, to enable measured net thrust to be corrected to a set of reference datum conditions that include still air (ISA sea level static), to obtain a corrected gross thrust.

Traditionally, this calibration has been carried out as a direct empirical back-to-back engine performance comparison between the indoor test facility and an outdoor free-field test facility, which has an assumed infinite atmosphere of still air. Unfortunately, due to an inconsistent UK climate and environmental issues such as pollution and noise, testing engines on an outdoor test facility has become limited, time consuming and costly, with inconsistent results. Also, the recent generation of large civil engines has outgrown the currently available "industry standard" outdoor test facilities, with evidence of ground effects and micro-climates being confirmed using investigative instrumentation and CFD modelling. A measurement uncertainty of approx. ±0.5% (random) plus –0.5% to –1.0% (systematic) in gross thrust is currently being estimated in these circumstances.

As an alternative to the free field method, the following first principles methodology has been developed and patented to derive the aerodynamic thrust correction for an indoor test facility “in situ”, using arrays of anemometers and static pressures in an extensive aerodynamic survey. This stand-alone methodology can be used in isolation or with reference to any other source, effectively relating an indoor test facility to free field using first principles.

The following Fig 1 illustrates a typical indoor “U” shaped sea level test facility with main features, airflow paths and an introduction to first principle measurement planes and positions.

Fig. 1. Typical Indoor “U” Shaped Sea Level Test Facility



2 Basic Method

The basic first principles method sums three drag forces that are opposing thrust measurement, namely inlet momentum, cradle and base drags. Further detail regarding the measurement apparatus, instrumentation requirements, calculations and assumptions associated with this method are contained in the following sub sections.

This basic method assumes that either there is no engine debris guard being used, or if there is, that it is attached to the live and moving part of the thrust measurement system.

In the event that a test facility has been designed with an engine debris guard that is fixed to the ceiling or floor and not attached to the live and moving part of the thrust system, pressure loss through the debris guard will reduce the inlet momentum drag felt by the engine, and hence increase measured thrust. In this case, it will be necessary to derive a 4th term as a drag “debit” by removing the debris guard and carrying out empirical back-to-back testing. This is necessary because the first principles measurement plane for inlet momentum drag is positioned upstream of this pressure loss plane. It is a future aim to derive this term using a pressure loss versus drag characteristic for a family of engines on a test facility that use the same debris guard.

2.1 Inlet Momentum Drag

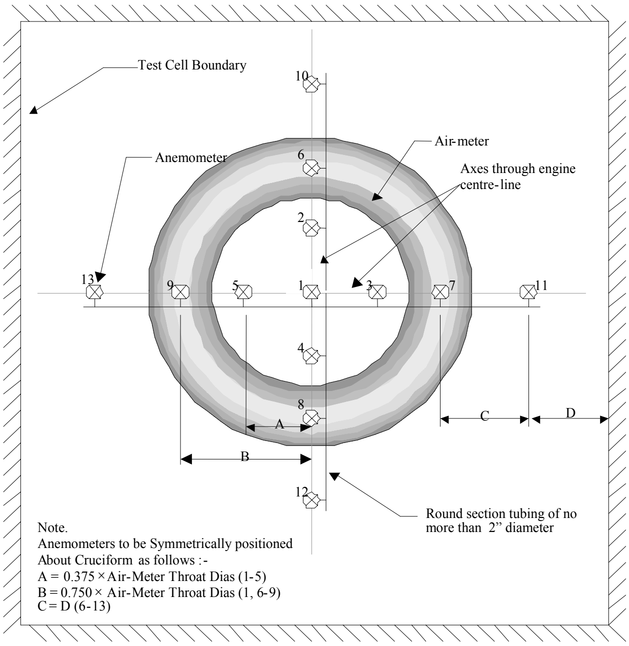
This is calculated from measuring the mean airflow approach velocity within the engine/intake “stream tube” using up to 9 shrouded anemometers (1-9) positioned in cruciform formation, axially positioned 2-3 air-meter throat diameters upstream of the front face of the intake bell mouth flare (see Fig 2).

This axial position is chosen for 2 reasons :-

- To only capture the test facility wind tunnel effect before any acceleration into the intake bell mouth flare occurs.
- To ensure that there is sufficient distance to allow any wakes from the measurement apparatus to re-mix, and hence not affect engine stability or performance.

The radial positions specified on Fig 2 ensure that at least 1.5 × air-meter throat diameters of approaching stream tube is captured for measurement.

Fig. 2. Upstream Anemometer Positions (Cruciform Formation)



Note:

- The 4 off additional anemometers (10-13) shown in Fig 2 are used for an overall aerodynamic stability survey and not these specific inlet momentum drag calculations.

In the case of engines with an air-meter throat diameter less than 1,5 meters, 5 anemometers are likely to suffice with the 0.375 throat diameter radius position anemometers (2-5) not being required.

This method enables the calculation of a basic area weighted average of airflow velocity that is considered acceptable for many applications. Any variation in airflow approach velocity profile about the 5 or 9 anemometers greater than ±15% from mean, is considered unacceptable.

Therefore Intake Momentum Drag **(1)**

$$= (W1 \times V0)/1000 \quad kN$$

Where:-

W1 =Observed engine inlet mass airflow - kg/s

V0 =Mean velocity of 1-5or9 anemometers - m/s

Note:

- Engine inlet mass airflow should be measured in a calibrated air-meter to within an accuracy of ±1.0%.

Fig. 3 illustrates a typical example of tubular cruciform apparatus to locate these forward anemometers.

Fig. 3. RB199 Engine at RAF Marham, UK

Alternatively, a similar but less intrusive method to locate the forward anemometers using pairs of taught wires can be seen on Fig 4.

Fig.4. Tay Engine at RR Dahlewitz, Berlin, Germany.

As a further alternative to the cruciform type of apparatus, a vertically traversing horizontal boom is currently being used to locate the forward anemometers in some of the large civil engine test bed applications.

This enables a much greater array of airflow velocity measurement in a larger arena, leading to a better understanding of inlet stream tube profile shape and the ability to carry out preferred mass momentum flow weighted averaging, using contour plotting and specialised software.

Figure 5 highlights a typical traversing boom measurement array with the basic cruciform formation and an approximated stream tube sized for a Trent 900 engine, shown for comparison.

Fig. 5. Typical Upstream Anemometer Positions (Traversing Boom)

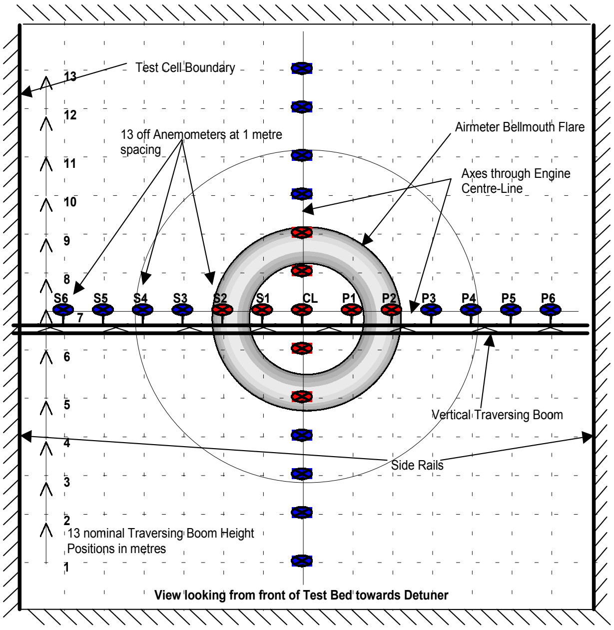


Figure 6 illustrates a typical traversing boom installation to locate the forward anemometers.

Fig. 6. Trent 900 Engine at RR Derby

One further advantage of using this traversing method is that a much better understanding of “full” test facility airflow profiles and hence future design capability can result from this greater array of measurement. This can also be used to support CFD modelling.

Typically, this inlet momentum term will account for between 70%-90% of the total thrust correction and hence, is by far the largest term.

If it is necessary to include the “fixed” debris guard drag debit term, this can typically reduce this inlet momentum drag term by up to 50%.

2.2 Cradle Drag

This is derived by calculating the pressure loading of entrained/by-pass cell airflow acting upon the frontal blockage areas of all live and moving parts of the test facility thrust cradle and attached obstructions. This pressure loading is calculated by measuring the airflow velocities adjacent to (approx. 10 cm from anemometer center line to blockage component edge) these frontal blockage areas, using up to 10 shrouded anemometers evenly spread around the thrust cradle and attached obstructions.

Deciding where to position these anemometers involves an element of judgment, since no two test facilities are likely to be exactly the same. If it is possible to achieve a reasonable symmetrical average spread, then calculated mean averages can be used as depicted in the following equation (2). However, if this is not possible or significantly differing cell airflow velocities are being seen around the thrust cradle, then individual anemometer values in conjunction with their respective adjacent blockage areas can be summed after being broken into separate components.

Therefore Pressure Loading (Δp) **(2)**

$$= P0 \left\{ 1 - \left(\frac{1}{1 + (6.0449 \times 10^{-6} \times V_{CELL}^{2})} \right) \right\} kPa$$

Where:-

P0 = Cell static pressure – kPa

V_{CELL}=Mean vel of up to 10 anemometers – m/s

Notes:

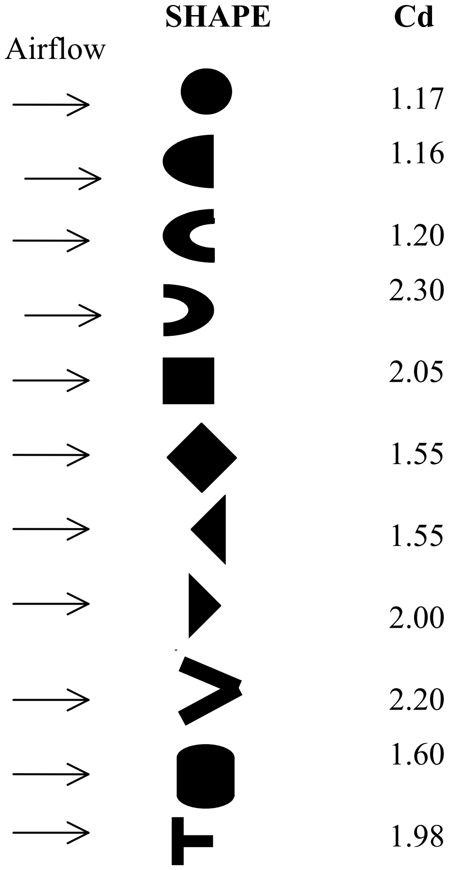
- The preferred position for cell static pressure measurement is approx 1 meter outboard from the test cell wall in the axial plane of the cold/hot nozzles at engine centre line height.
- The constant contained in equation (2) above fixes the cell static temperature at an ISA day value in conjunction with the speed of sound. This is done to eliminate the need to measure and calculate local cell static temperatures that would be required for the traditional Bernoulli equation ($\frac{1}{2}\rho V^2$). The measurement uncertainty associated with this has been approximated as ±0.01% in gross thrust for an ambient temperature change of ±20 K on EJ200 and is considered negligible.

The total frontal geometric blockage area of all moving elements of the test facility thrust cradle and attached obstructions must be measured. If any blockage elements are shielded by further upstream blockage, then it is recommended that they should not be counted unless they are greater than 5 obstruction widths downstream of the upstream blockage. Also, it is recommended that flexible components such as hoses, cables and tubes should not be counted, because any potential drag effects are likely to be negligible.

A mean Cd that relates to this total thrust cradle blockage area needs to be calculated. The respective shape Cd's can be acquired by reference to Hoerner's Fluid Dynamic Drag – Chapter V111 (interference drag).

Fig 7 illustrates some typical reference Cd values used :-

Fig. 7. Example Reference Cd's to be used for Varying Thrust Cradle Blockage Area Shapes



Therefore Cradle Drag **(3)**

$$= \Delta p \times A_{CRAD} \times Cd_{CRAD} \quad kN$$

Where:-

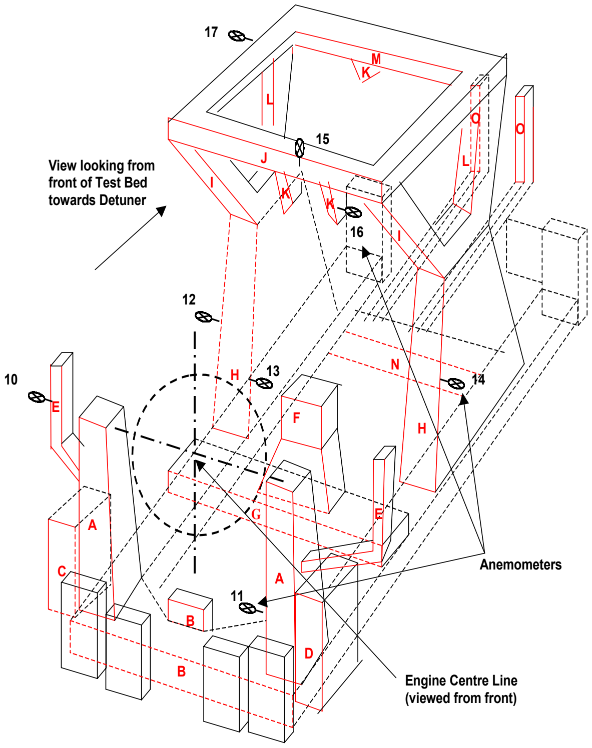
Δp = Pressure loading as equation 2 - kPa

A_{CRAD} = Meas total frontal blockage area – m^2

Cd_{CRAD} = Calculated mean blockage area Cd

Two examples of anemometer positions, measured cradle blockage area and calculated respective Cd's are shown on Figs 8 & 9 respectively

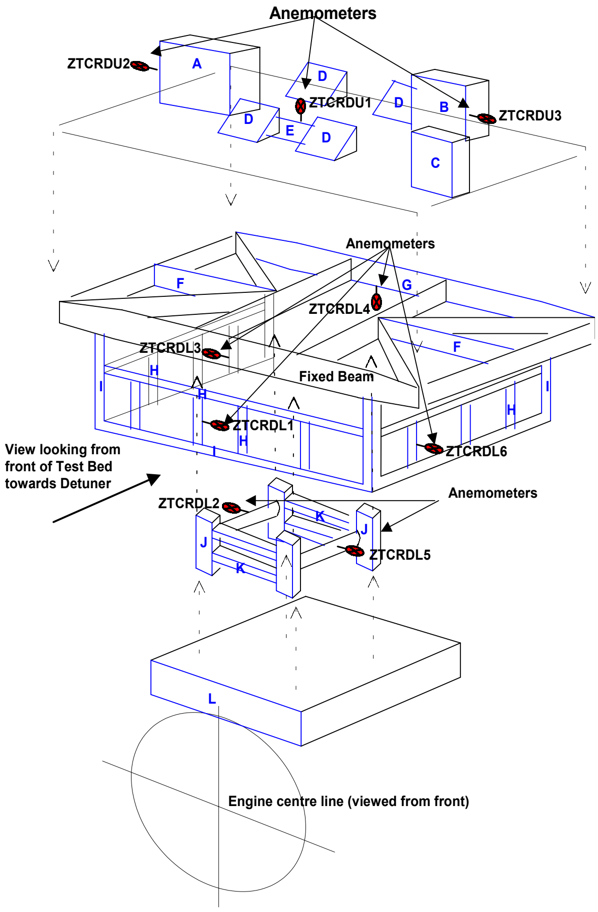
Fig. 8. EJ200 Engine Floor Mounted Thrust System at RR Bristol



Note:

Geometric Blockage Area	Square Metres	Cd
A-E Total	=(0,8628)	Mean =(2.00)
F-K Total	=(1,5272)	Mean =(1.87)
L-O Total	=(0,645)	Mean =(1.92)
Overall Total	**=(3,0350)**	**Overall Mean =(1.92)**

Fig. 9. Trent 800 Engine Overhead Mounted Thrust System at RR Derby



Note:

Geometric Blockage Area	Square Inches	Cd
A-E Total	=(6942)	Mean =(1.81)
F-K Total	=(17832)	Mean =(2.02)
L Total	=(1056)	Mean =(1.60)
Overall Total	**=(25830)**	**Overall Mean =(1.95)**

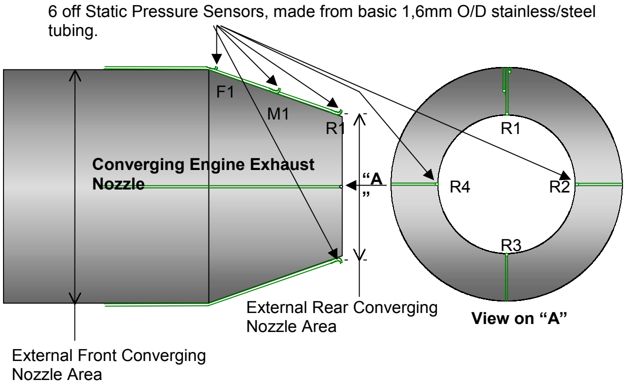
Typically, this cradle drag term is likely to account for between 5-25% of the total thrust correction.

Whilst this term is associated with test facility hardware only, if it is judged that some engine or slave test hardware components constitute potential additional drag, then they should be counted as a separate drag using similar techniques and calculations as used for this drag term.

2.3 Base Drag (Detuner Suction)

This is derived from calculating the mean static pressure depression as a result of accelerating entrained/by-pass airflow velocities as they flow over the convergent exhaust nozzle to enter the detuner. The ejector creates a suction force that can be calculated using Δp × area change. This Δp is calculated from measuring the mean static pressure from at least three equal axial planes (front, mid, rear) along the outer skin of the conical section of the exhaust nozzle, with the final position being measured by at least 4 circumferential sensors to evaluate profile/ejector effectiveness in an overall aerodynamic survey (see Fig 10).

Fig. 10. Typical Convergent Nozzle Static Pressure Arrangement Configuration



Notes:-

- Static pressures to be positioned as shown with the end turned to be normal to the airflow by no more than approx. 7mm.
- Mean converging nozzle static pressure equates to the mean of the 3 planes F,M&R, noting that the station R will be the mean of at least 4 sensors R1-R4.

A much greater array of static pressure measurement can be considered for more critical or complex shape applications.

$$\textbf{\textit{Therefore Base Drag}} \qquad \textbf{(4)}$$

$$= (P0 - P7.5) \times (A7 - A8) \quad kN$$

Where:-

P0 = Cell static pressure (as equation 2) – kPa

P7.5 = Mean conv nozzle static pressure *– kPa*

A7 = External front conv nozzle area – m^2

A8 = External rear conv nozzle area – m^2

Fig 10 illustrates a typical single nozzle configuration for a turbojet or mixed turbofan. In the case of a non-mixed separate jet turbofans, where detuner entrained cell airflow is not in direct contact with the hot exhaust nozzle skin, this term only applies at the forward cold nozzle position.

If the test facility detuner is a telescopic design, then it is possible to optimise the ejector effect and hence, reduce local airflow velocities and thrust drag terms to a level that is aerodynamically preferable overall. This includes ensuring that no hot gas is spilled into the test cell that can be re-ingested by the engine, which can be measured during an overall aerodynamic survey.

Two examples of nozzle static pressure applications are shown on Figs 11 & 12 respectively.

Fig. 11. EJ200 Mixed Single Nozzle Static Pressure Application at RR Bristol

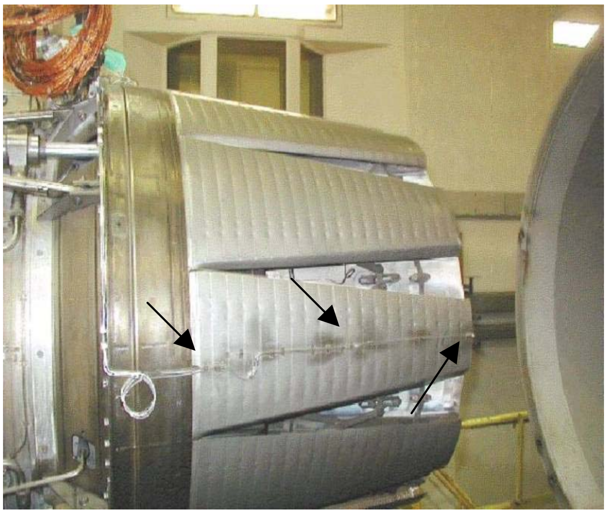
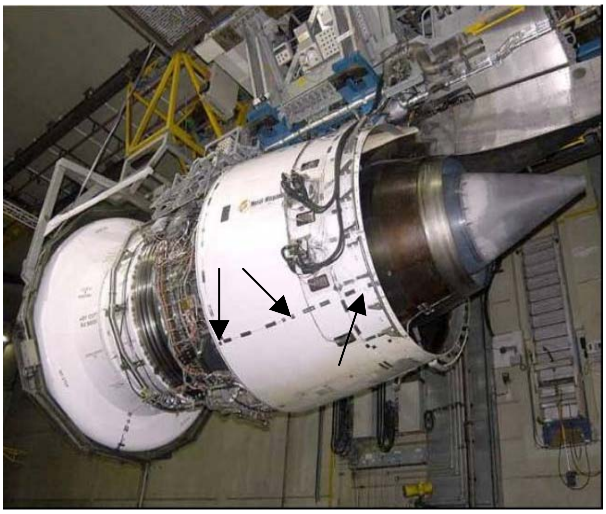


Fig. 12. Trent 900 Separate Jet Cold Nozzle Static Pressure Application at RR Derby



2.4 Total Drag (Overall Aerodynamic Thrust Correction)

This is simply the sum of the former three components and can be converted into an overall aerodynamic thrust correction characteristic, which can be deployed in a performance pass-off or analysis software programme, preferably as a correlation against measured thrust or inlet flow function.

Typically, this total drag term is likely to be in the region of 1-8% of gross thrust, depending on engine size in relation to it's test facility.

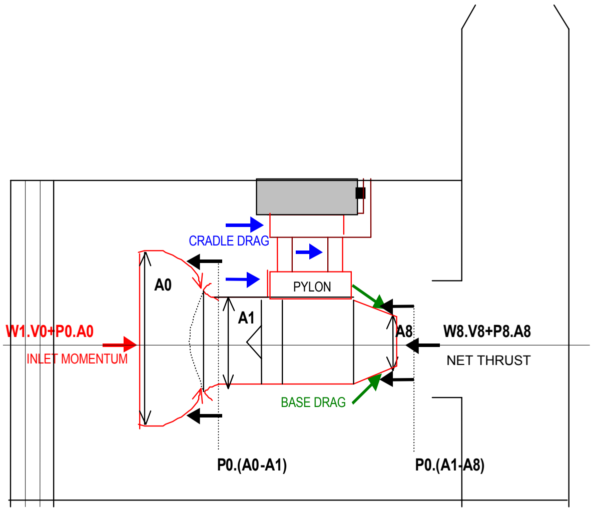
A measurement uncertainty of less than ±0.25% in gross thrust is currently estimated for this method. This will increase to approx. ±0.30% if the test facility has a "fixed" debris guard that necessitates deriving the additional 4th component previously discussed (debris guard debit drag).

2.5 Basic Method Assumptions

The basic method assumes a static pressure field equilibrium throughout the test cell and hence "control volume" thrust momentum box (which includes the forward anemometer plane) – see Fig 13.

This assumption is considered acceptable for test cell applications in which the airflow velocity is stable, uniform and in the region of 30 ft/sec or less, with an entrainment ratio greater than 2 to 1 and an overall aerodynamic thrust correction of 4% or less. In these cases it is believed that any additional or unaccounted forces, particularly P0(A0-A1) and P0(A1-A8) shown on Fig 13 are considered negligible (<0.1% of gross thrust), and therefore cancel in the following equation (5).

Fig. 13. Current Basic "First Principles" Method Control Volume Assumptions



Notes:

- The potential force P0.(A1-A8) represents any buoyancy forces acting on the engine due to the reduction in area (front to rear), assuming all external static pressure is P0
- The potential force P0.(A0-A1) has two parts:
  1) The force acting upon the rear of the bellmouth flare
  2) The axial momentum lost by the engine stream tube flow, due to the turning of the stream lines

Therefore Gross Thrust **(5)**

$$= W8.V8+P8.A8 - P0.(A1\text{-}A8) - P0.(A0\text{-}A1) + (W1.V0+P0.A0) + \text{Cradle Drag} + \text{Base Drag}$$

$$= W8.V8 - (P8-P0)A8 + W1.V0 + \text{Cradle Drag} + \text{Base Drag}$$

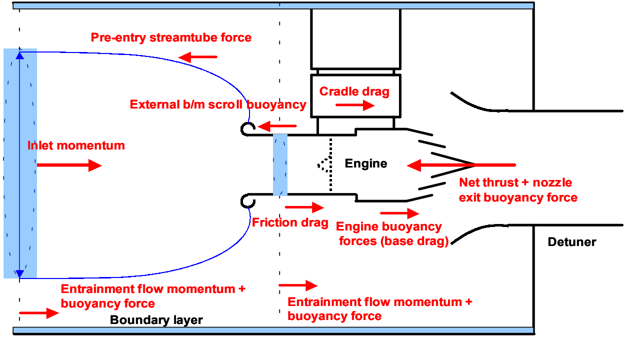
$$= \text{Net Thrust (measured)} + \text{Inlet Momentum} + \text{Cradle Drag} + \text{Base Drag}$$

3 Revised Full Method

Current industry standard large civil engine indoor test facilities are unlikely to be able to achieve the aerodynamic requirement assumptions listed for the basic method, particularly regarding minimum airflow velocity. This, coupled with the likelihood of a tighter uncertainty assessment requirement for customer compliance demonstration, necessitates a far more rigorous assessment of any potential additional and unaccounted forces that are deemed negligible with the basic method.

Therefore, the additional terms deemed negligible and shown on Figure 13 are likely to become more significant and need to be quantified as additional engine buoyancy forces. Figures 14A & B illustrate a revised full control volume thrust momentum box in description and equation form respectively, that enable first principles thrust correction to be aligned with other methods ("ideal free field" or "nozzle rig"), and thus "thrust in flight" accounting during civil engine compliance demonstration to the customer.

Fig. 14A. Revised Full "First Principles" Method Control Volume Assumptions



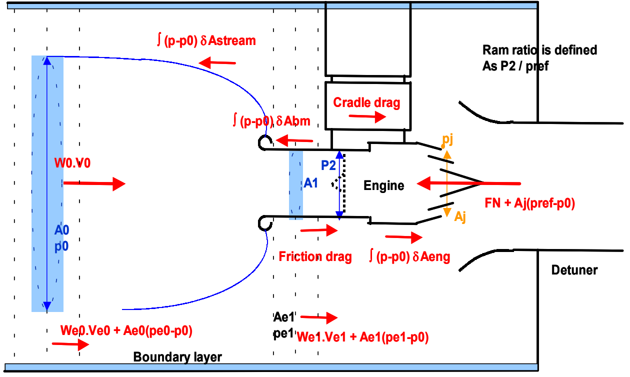
Note:

- Pre-entry streamtube force (including rear bellmouth scroll buoyancy force) can be estimated from entrainment flow, = Entrainment momentum (1) + Entrainment buoyancy force - Entrainment momentum (0)

Therefore Gross thrust **(6)**

= Net thrust + Inlet momentum - Pre-entry streamtube force – External b/m scroll buoyancy + Engine buoyancy forces + Cradle drag + Friction drag - Nozzle exit buoyancy force

Fig. 14B. Revised Full "First Principles" Method Control Volume Assumptions



Note:

- ∫ (p-p0) δAstream (including rear bellmouth scroll buoyancy force) = We1.Ve1 + Ae1(pe1-pe0) - We0.Ve0

Therefore Gross thrust **(7)**

= FN + W0.V0 - ∫ (p-p0) δAstream - ∫ (p-p0) δAbm + ∫ (p-p0) δAeng + Cradle drag + Friction drag - Aj(pref-p0)

Where:-

*pref = pj * (p0 "free-field" / pj "free-field") for "free-field" nozzle coefficient accounting, and from entrainment flow*

The following additional requirements (relative to the basic method) need to be considered in order to enable the derivation of the additional terms :-

- Derive the stream tube pre-entry force using CFD model integration or simple 1D entrainment flow calculation (not directly measurable).
- Derive the bell mouth buoyancy (pull-off) term also using the CFD or 1D calculation as above.
- Fit static pressure measurement sensors (p0) at the traversing boom (A0) plane.
- Fit static pressure measurement sensors to the rear face of the bell mouth scroll.
- Fit static pressure measurement sensors (pj) at the (Aj) plane. This can be achieved using an existing design of piezo-ring, which is additional to current base drag static pressure measurement.

From this information, the following additional terms can now be quantified :-

- Pre-entry stream tube force (turning stream lines) from CFD and/or 1D calculation.
- Pre-entry stream tube force (bell mouth pull-off) from CFD and/or 1D calculation and/or measured static pressure Δp (bellmouth – boom (p0)).
- Nozzle exit buoyancy force from CFD and/or measured static pressure Δp ((pref) – boom (p0)).
- Engine buoyancy forces shown are currently represented by base drag in the basic method.
- Friction drag is considered negligible.

Notes:-

- pref is determined from pj with a correction defined from free field or noxzzle rig.
- pref is also used for ram-ratio definition corrections in the engine performance synthesis model.
- p0 should now replace cell pressure as the datum for basic method cradle and base drags.

Some of the above terms are self-canceling. However, the net result provisionally defined on RR's highest flowing engine in its master test facility (Trent 900) was between –0.2% & -0.3% of gross thrust relative to the basic first principles method.

It should be re-iterated that when testing smaller low flow engines in the regime described for the basic method, this is more likely to be in the region of -0.02%.

4 Advantages and Benefits of using First Principles

- **Significant Quality Improvements** - Derived thrust correction uncertainty (including repeatability) improved from an estimated ±0.8% to ±0.25%. This alone has led to improved customer satisfaction.
- **Major Cost Benefits to Eliminating Outdoor Testing** – Demonstrated during successful compliance demonstration for the Gulfstream G450 aircraft programme (see also reasons next bullet).
- **Major Lead Time Benefits to Eliminating Outdoor Testing** – Estimated to be in the region of 3-6 months per installation. This includes eliminating two of the calibration legs in a B-A-B type cross-calibration and the time taken waiting for acceptable environmental conditions in a typical inconsistent UK climate.
- **Ability to Calibrate an Indoor Test Facility from "Day One" of a New Engine Project** – This has previously taken up to two years before the formal customer compliance demonstration is carried out, thus carrying significant risk well into the programme.
- **Major Cost and Lead Time Benefits to Eliminating Regular Indoor Test Facility Cross-Calibration** – Ability to re-calibrate indoor test facilities (including masters) at any time "in situ", without reference to any other source, thus eliminating expensive A-B-A type back-to-back testing.
- **Ability to Identify and Quantify Test Facility Aerodynamic Design Problems** – The vast array of acquired measured aerodynamic data is helping to identify problems from the outset and diagnose instant corrective action, thus avoiding the traditional and more expensive time consuming culture of "try it and see" fixes.
- **Ability to Support the Next Generation of Improvements** – The vast array of acquired measured aerodynamic data is also enabling better CDF modeling of test facility design, with the potential future ability to be able to predict thrust correction accurately.