AEROSPACE INFORMATION REPORT

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Test Cell Thrust Measurement

RATIONALE

This SAE Aerospace Information Report (AIR) has been written for individuals associated with ground level testing of large and small turbofan and turbojet engines who are interested in thrust measurement systems and the factors that influence thrust measurement accuracy.

1. SCOPE

Thrust measurement systems come in many sizes and shapes, with varying degrees of complexity, accuracy and cost . For the purposes of this information report, the discussions of thrust measurement will be limited to axial thrust in single-axis test systems.

1.1 Purpose

There are several purposes served by this information report:

a. To provide guidelines for the specification of thrust measurement systems.

b. To address the major factors which can influence thrust measurement uncertainty.

c. To consider the operational characteristics and the effects on system performance.

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 the 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 ASME Publications

Available from American Society of Mechanical Engineers, 22 Law Drive, P.O. Box 2900, Fairfield, NJ 07007-2900, Tel: 973-882-1170, www.asme.org.

ASME 86-WA-DE-3 Evaluating and Testing of Turbofan Jet Engines, miller, T.M., 1986

ASME PTC 19.1-2006 Test Uncertainty

2.1.2 ISO Publications

Available from International Organization for Standardization, 1, rue de Varembe, Case postale 56, CH-1211 Geneva 20, Switzerland, Tel: +41-22-749-01-11, www.iso.org.

ISO/IEC Guide 98-1-2009 Uncertainty of measurement - Part 1: Introduction to the expression of uncertainty in measurement

ISO/IEC Guide 98-3:2008 Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

2.1.3 Other Publications

Covert, E.: "Thrust and Drag: Its Prediction and Verification", Volume 98, Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, 1985.

Ashwood, P.F. et al.: "Operation and Performance Measurements on Engines in Sea Level Test Facilities", AGARD Lecture Series No. 132 (AGARD-LS-132), Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, Neuilly-sur-Seine, France, 1984.

Stroud, J.F.: "Propulsion System Testing Requirements for a Commercial Transport", AGARD CP-293, 1981.

Roberts, J.H., et al.: "Engine Thrust Measurement Uncertainty", AIAA 85-1404, 1985.

MacWhorter, R.F.: "F404-GE-400 NARF Engine Test Cell Mount System Vibration Test", General Electric Component Development Laboratory, TN4759, 1981.

2.2 Definitions

ANGULAR LOAD, CONCENTRIC: A load applied concentric with the primary axis at the point of application and at some angle with respect to the primary axis.

ANGULAR LOAD, ECCENTRIC: A load applied eccentric with the primary axis at the point of application and at some angle with respect to the primary axis.

AXIAL LOAD: A load applied along or parallel to and concentric with the primary axis.

CALIBRATION: The comparison of thrust frame output to a standard load. A calibration curve is obtained by performing a calibration at a number of increasing and decreasing load points.

COMBINED ERROR: The maximum deviation of output from a straight line drawn between the no-load and rated load outputs expressed as a percentage of the rated output and measured on both increasing and decreasing loads.

COMPENSATION: The use of supplementary devices, materials, or processes to minimize known sources of error.

CREEP: The change in load cell output occurring with time while under a constant load condition and with all environmental conditions remaining constant. Usually measured at the rated load and expressed as a percentage of the rated load over a specific period of time.

DEFLECTION: The change in length along the primary axis of the load cells between no-load and rated load conditions.

ERROR FACTORS: Systematic and random differences between the measured and true value of the parameter being measured, the combination of which comprise the measurement uncertainty.

EXCITATION, ELECTRICAL: The voltage or current applied to the terminals of the load cell.

FLEXURE: A plate or cylinder incorporating two areas of reduced thickness (webs) which act as pivots. Each pivot allows a rotation or pivoting action as the result of elastic deformation in the areas of reduced thickness.

GROUND FRAME: The part of the thrust frame structure which is rigidly attached to the building feature such as the roof or a foundation. It is also referred to as the fixed frame.

HYSTERESIS: The maximum difference between output readings for the same applied load, one reading being obtained by increasing the load from zero, and the other by decreasing the load from the rated load. It is usually measured at 50% of the rated load and expressed as a percentage of the rated load.

LIVE FRAME: The part of the thrust frame structure which is suspended from the ground frame by the flexures. It is also referred to as the floating frame.

LOAD: The force applied to the load cell.

LOAD CELL: A device which produces an electrical signal proportional to the force applied to it.

MEASUREMENT UNCERTAINTY: The difference between the measured value of a physical quantity and the true value of the same physical quantity.

NON-LINEARITY: The maximum deviation of the calibration curve from a straight line drawn between the no-load, and rated load outputs, expressed as a percentage of the rated load, and measured on increasing load only.

OVERLOAD RATING, SAFE: The maximum load, in percent of rated capacity, which can be safely applied without producing a permanent shift in the performance characteristics beyond those specified.

PRIMARY AXIS: The axis along which the load cell is designed to be loaded; normally its geographic centerline.

RATED LOAD: The maximum thrust the thrust frame is designed to measure. Also referred to as rated capacity.

REPEATABILITY: The maximum difference between individual thrust frame output readings for repeated loadings under identical load and environmental conditions.

RESOLUTION: The smallest change in load input which results in a detectable change in output.

SENSITIVITY: The ratio of the change in output to the change in mechanical input.

SHUNT CALIBRATION: The electrical simulation of load cell output by known shunt resistors between appropriate points within the circuitry.

SIDE LOAD: Any load acting perpendicular to the primary axis at the point of the load application.

TEMPERATURE RANGE COMPENSATED: The range of temperature within which the load cell is compensated to maintain rated output and zero balance within specific limits.

TEMPERATURE COEFFICIENT: The change in load cell output per unit change in temperature at a constant load condition and with all other environmental conditions remaining constant. Usually specified as effect on sensitivity in % of reading /ΔT and effect on zero in % of rated output/ΔT.

THRUST STAND: Test cell fixture used to support and interface with the engine adapter. Consists of ground and live frames and contains the thrust measurement and in-frame calibration system components. Sometimes referred to thrust frame or test stand.

ZERO BALANCE: The output signal of the load cell with rated excitation and with no-load applied, usually expressed in percent of rated output.

ZERO SHIFT: A change in the no-load output.

3. THEORY OF THRUST MEASUREMENT

The basic challenge of thrust measurement in a test cell thrust stand is that the engine develops its thrust on the engine centerline. It is not feasible to mount thrust measurement equipment on centerline either in front of the engine under test, where it would disturb the engine intake air, or behind it, where it would be in the hot and high-velocity exhaust stream.

The practical solution is to provide a thrust stand, which consists of a pair of rigid frames that are designed to support and constrain the engine under test in such a way that it is possible to measure the thrust of the engine without placing any obstacles in the engine air paths. The thrust stand has a fixed element, which is attached to the ground or to some part of an enclosing building (a test cell), and a moving element (sometimes called the live or floating frame), which carries the engine under test. The moving element of the thrust stand is supported from the fixed element by some means which will carry the weight of the moving element and the engine under test, yet will move as freely as possible in response to the engine's thrust. The thrust produced by the engine is transmitted, through a force measuring device, from the moving element of the thrust stand to its fixed element, and thence to the ground or to the building which houses the thrust stand. A typical overhead thrust stand configuration for gas turbine engine testing is shown in Figure 1.

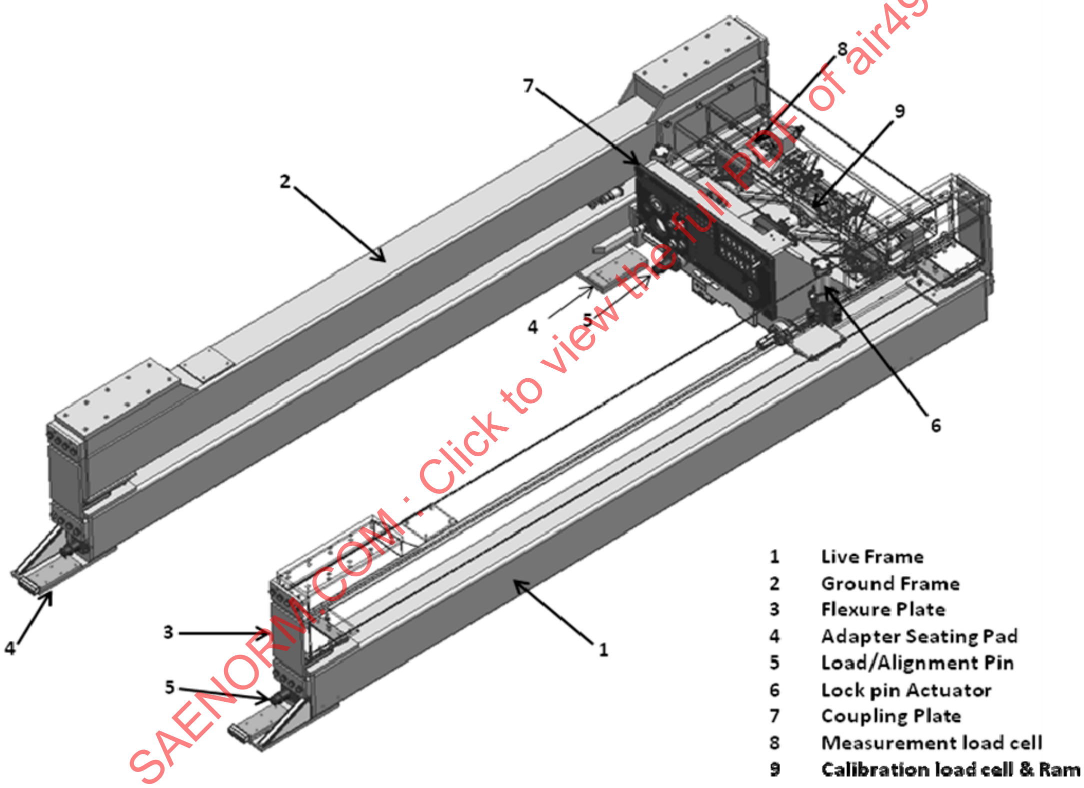

FIGURE 1 – THRUST FRAME CONFIGURATION

The mechanical design of the thrust stand may require that the engine thrust be measured with a single load cell in tension, a single load cell in compression, a pair of load cells in compression or a pair of load cells in tension. When utilizing a pair of load cells, the load cell outputs are summed to obtain the applied load. Some systems that accommodate a wide range of engine thrusts incorporate "stacked" load cells that consist of axially connected low and high range load cells. When utilizing a stacked load cell arrangement care must be taken not to overload the lower range load cell, which is usually accomplished by mechanical stops internal to the load cell, and to consider in the uncertainty analysis the side load applied to the high range load cell by the attached and overhung low range load cell.

Preload may applied to the thrust stand floating frame to reduce certain error factors of thrust measurement uncertainty or to provide reverse thrust measurement capability. Typically, preload is mechanically or hydraulically applied, independently measured and subtracted from the measured thrust. Preload can be applied as either a constant force in the forward thrust direction or as a force equally applied to opposing load cells, resulting in minimal floating frame deflection at no applied thrust. The applied preload may compensate for zero offsets due to the mass and center of gravity of different engine/adapter combinations. With opposing load cells, the subtraction can reduce the effect of load cell temperature changes, especially if the measurement and preload load cell temperature coefficients are closely matched. In systems with a constant preload the preload value is usually set to 10% – 15% of the measurement range. In a system with opposing load cells the preload is typically set to a value equal to 55% to 60% of the thrust measurement range, which will ensure the preload does not unload at maximum thrust.

Figure 2 is a basic schematic (free-body) representation of the moving element of a thrust stand and the forces which act on it.

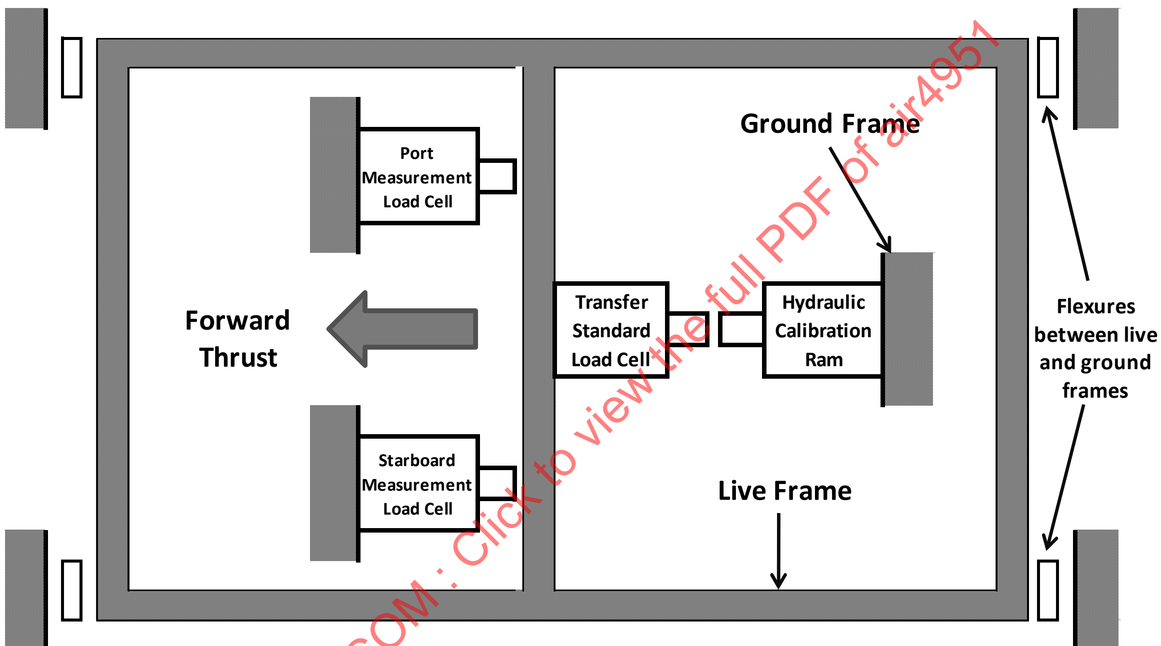

FIGURE 2 - DIAGRAM OF MOVING ELEMENT

The engine thrust and the thrust measuring system produce a substantial couple (torque) which, in this case, causes an upward force at the front of the thrust stand and a downward force at its rear. With good design these are almost purely vertical forces. Thrust stand designers exert great care to minimize any horizontal (axial) components of force which are transmitted by the apparatus which supports the moving element of the thrust stand. In this way the force measured by the load cell(s) is very nearly equal to the actual thrust of the engine under test. The cosine law relationship between the engine (and therefore thrust) centerline and the horizontal component of thrust means that small angular displacements of the engine will have minimal effect on the measured thrust.

3.1 Thrust Measurement Uncertainty

As with all other engine operating parameters which are to be observed during an engine performance test, each engine manufacturer specifies the allowable uncertainty with which thrust must be measured. Typical OEM specifications require thrust measurement system accuracy in the range of 0.10% to 0.35% of reading at maximum takeoff thrust.

Basic test cell thrust measurement is only one element of the overall uncertainty that is applicable in establishing the gross thrust of an engine in an indoor test cell. For indoor ground-level testing of jet engines, the aerodynamic forces in an indoor test cell influences the thrust produced by the engine. The "true" gross thrust may be derived from the measured thrust if the aerodynamic conditions inside the test cell are established. 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.

4. APPLICATIONS

As with any measurement system, the type of thrust system used varies with the application requirements. The applications can vary from commercial to military situations, production to development test cells, small turbojets to large turbofans. The application not only determines the size of the thrust measurement system, but also the configuration, the accuracy requirements, and the cost. The thrust measurement system is made up of many individual parts, both mechanical and electrical, and is only as accurate as the least accurate part of the entire system.

There are many factors which influence the thrust measurement system requirements which are governed by the particular application, such as: engine diameter and weight, time for installation, access to engine ancillary equipment, etc.

5. THRUST STAND CONFIGURATIONS

Thrust stands generally fall into two categories: underslung (floor-mounted), and overhung (overhead).

Underslung thrust stands, such as the one shown in Figure 3, are used mainly for military engines and small commercial engines up to the 30 000 pound (133 kilonewton) thrust class. An underslung thrust stand is relatively light and simple. It may be mounted on a rugged cart which is tied down during an engine test or it may be fixed to the floor of a test cell. The engine to be tested may be rolled onto, or hoisted onto, the stand's support rails.

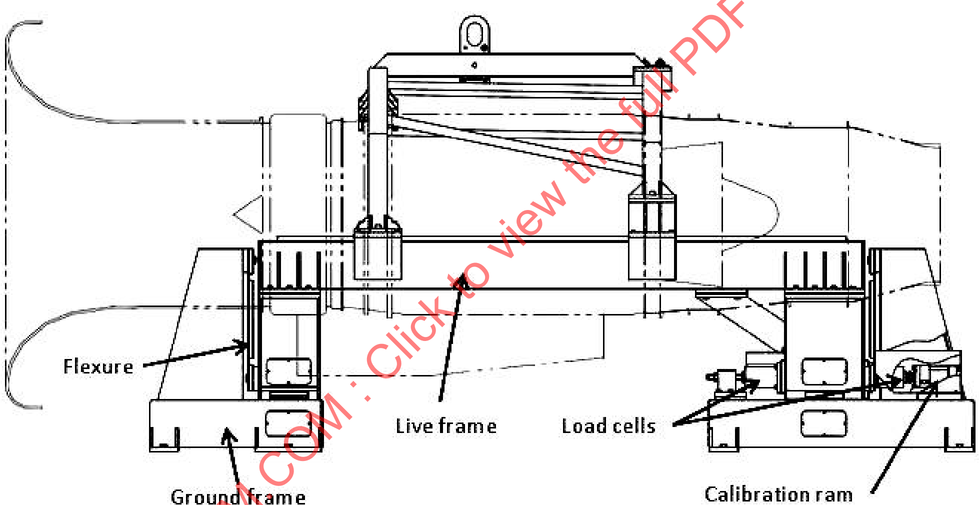

FIGURE 3 - UNDERSLUNG THRUST STAND

By contrast, overhung thrust stands (Figure 4) are mounted to the ceiling of a test cell or to some other overhead structure, and typically are larger and heavier than the underslung type, as they are used with the largest turbofan engines; some are rated for thrusts up to 150 000 pounds (667 kilonewtons). The engine for test may be delivered on a cart and hoisted into the thrust stand, or delivered to the stand by an overhead monorail system. One advantage of the overhung thrust stand is that it gives easy access to the engine accessories, which are commonly mounted on the underside of the engine.

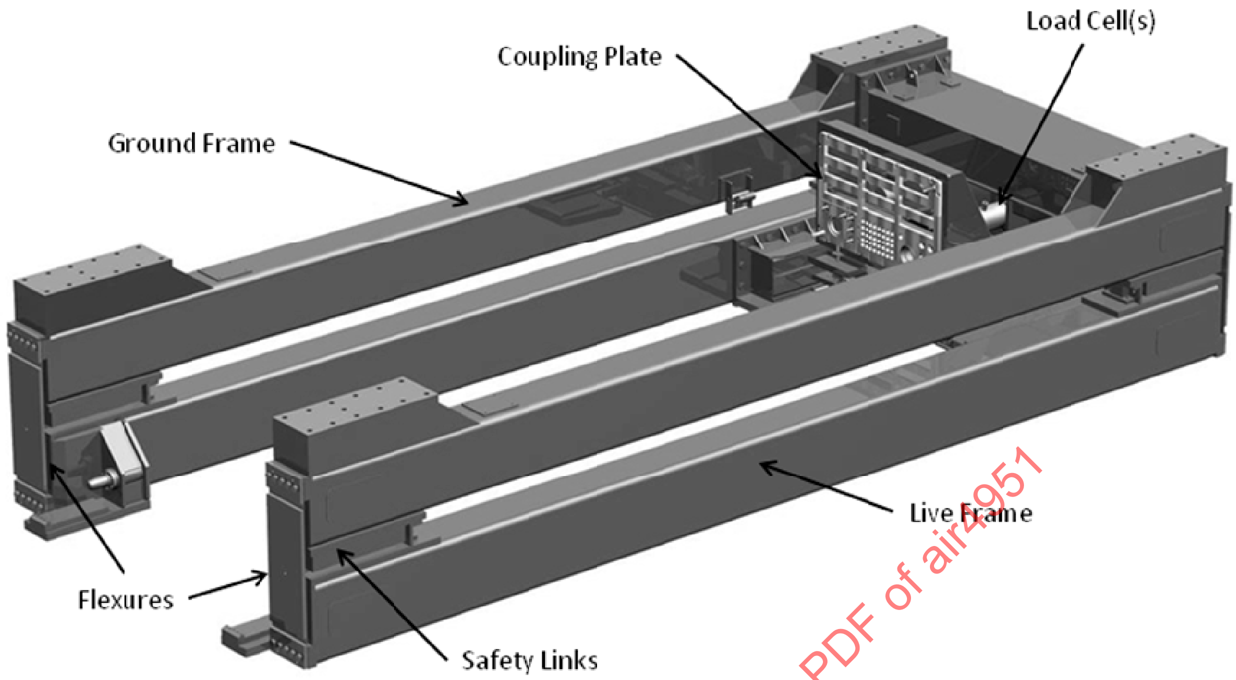

FIGURE 4 - OVERHUNG THRUST STAND

5.1 Engine Mountings

The engine to be tested is usually attached to the moving element of the thrust stand by means of the normal engine mounts which are used to support that type of engine on an aircraft. A thrust stand that will be used to test several different engine models will usually have a neutral design, using a mechanical adapter for each engine type to carry the engine in the same way in which it will be supported on the wing, which differs greatly between engine models. Some engines may require adapters with specific mounting attachments, such as a side mounting.

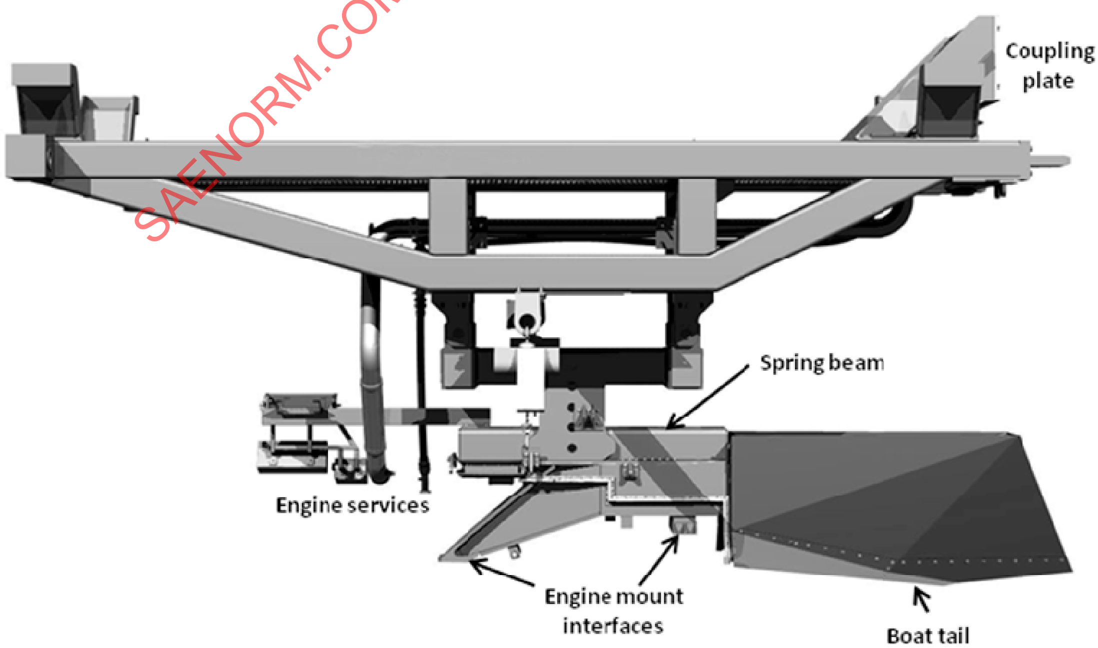

FIGURE 5 - TYPICAL OVERHUNG THRUST STAND ENGINE MOUNTING ADAPTER

The engine manufacturer may specify some special requirements related to the mounting of an engine. For example, some commercial OEMs specify that engines must be supported with mechanical structures having controlled spring rates that duplicate the flexibility of the airframe pylon, while other specify a “hardback” arrangement, i.e., a rigid mounting system. Boat tails with specific airflow lines may be required to simulate the airframe pylon. Engines which are used in tail-mounted pairs may be required to be supported for test at a small angle from the thrust stand axis.

5.2 Support of the Moving Element of the Thrust Stand

Several different techniques have been used for supporting the moving element of the thrust stand from the fixed element. It is important that the support system be relatively flexible in the direction of the engine's thrust force; usually it is also desirable that the support system be relatively stiff in the transverse direction. It must be strong enough to carry the weight of the engine, adapter and the moving element of the thrust stand, both under normal conditions and under abnormal loads such as the severe unbalance forces produced by loss of two or three fan blades from the engine under test, or by fault conditions such as interference between the compressor rotors and stators.

Almost all current thrust stand designs use flexure plates to support the moving element of the thrust stand. The flexure plates are made long enough and thin enough to have a relatively small axial spring constant, but transversely they are very stiff. The flexure plates must withstand large forces under fault conditions, yet their spring constants must be made as small as possible. The spring action is largely compensated for in the process of thrust calibration; see section 7.3. Various designs of flexure plates are available, including flat plate flexures and folded flexures.

The small safety factor that is typically used in flexure plate design for catastrophic failure loads increases the probability that a flexure plate may break under fault conditions, and therefore it is usual practice to provide a safety link in parallel with each flexure plate to carry the load in the event of a flexure plate failure. The two parts of a safety link cannot be permitted to touch each other in normal operation, as friction between the parts will disturb the thrust measurement. Any foreign material entering the gap in a safety link may also produce such friction. It is important to inspect and clean these gaps regularly.

6. DESIGN CONSIDERATIONS

Accurate measurement of engine-developed thrust requires that the load cell (or other force-measuring transducer) be aligned parallel with the engine centerline so that no significant off-axis forces (side loads) be applied to the load cell. Any axial forces, other than the engine thrust, that are applied to the moving element of the thrust stand must be minimized and be reproducible. Reproducibility permits undesired axial forces to be cancelled out during working thrust calibration.

6.1 Rigidity

Both the moving element and the fixed element of the thrust stand must transmit the full engine thrust, gravitational loads, normal & abnormal torque about the engine axis, normal & abnormal radial rotating loads, and the couple produced by the offset between the engine centerline and the axis of the thrust measurement transducer. These forces produce corresponding deflections of the thrust stand parts. Careful design is required to ensure that these deflections do not disturb the alignment of the load cell, apply non-axial forces to it, or upset the proper functioning of the flexure plates that support the moving element of the thrust stand.

In some cases, the fixed element of the thrust stand (the ground frame) may obtain a portion of its required rigidity from the structure to which it is attached, simplifying its design. Building rigidity and stability under load, vibration (including adjacent facility vibration) and temperature change can be an important factor.

6.2 Induced Vibration

All gas turbine engine produce vibrations. The dominant vibrations are at rotor frequencies and their harmonics, produced by rotor unbalances; although engine accessories, bearings, etc. may also produce vibrations, their effects on thrust stand design are relatively minor. It is important that the thrust stand structures should have no natural resonances which can be excited by rotor unbalances and can result in dynamic thrust measurement error (see 8.2.1.5) Such resonant vibrations can also be coupled back into the engine under test, increasing the engine vibration measurements to falsely high values.

To avoid dynamic error and false vibration data (or, in extreme cases, structural damage) due to resonances, the thrust stand resonance must be damped in some way, or (more commonly) moved out of the rotor-excited frequency range by adding mass or stiffening.

The frequency range of rotor-unbalance induced vibrations can be calculated from knowledge of the range of rotor speeds of the engines to be tested on the thrust stand. The possible resonances of the thrust stand can be computed by a structural analysis, or measured by a resonance survey.

6.3 Resonance Survey

Typical resonance surveys are made by striking the various parts of the thrust stand with an instrumented mallet and observing the resulting vibrations with accelerometers mounted on the thrust stand and connected to a spectral analyzer. The mallet impacts, in various directions and at different locations, will excite all significant resonance modes. The resonance survey should be made with the engine installed, as it could affect the results.

7. THRUST CALIBRATION

As with any instrumentation, it is necessary to calibrate the thrust measurement system regular intervals to maintain its operational accuracy. Calibration requires a means of producing simulated thrust and an independent force measuring system (the thrust calibration system) through which the simulated thrust is transmitted to the movable element of the thrust stand. A range of applied calibration forces is then compared to the readings of the working thrust measurement system.

The two broad classes of calibration methods are the in-frame method and the centerline method. In the in-frame method, the simulated thrust is applied between the fixed element and the moving element of the thrust stand; in the centerline method, the simulated thrust is applied at engine centerline level between ground (or building frame) and a calibration fixture which is temporarily mounted in the thrust stand in the same way in which an engine under test would be mounted.

7.1 Thrust Calibration System

The thrust calibration system functions as a secondary standard for force measurement. As such it must be stable and reliable, and its own calibration must be traceable to a national standards laboratory. Typically a transfer standard (calibration) load cell is recalibrated periodically in a lab in order to maintain its status. Commonly it is observed that its rate of change decreases with age, so that the frequency of recalibration can be reduced as time goes on and confidence in its stability increases.

The best practice is to send the calibration load cell and electronic signal conditioner/indicator together as a matched pair to the calibration laboratory for multi-point calibration.

The maximum extent the transfer standard load cell should be calibrated with the same mechanical features and adapters, such mounting brackets, base plates, load buttons or studs, etc., as used in the thrust stand, and they should remain installed during the process.

In using the thrust calibration system, additional accuracy can be gained by use of the error curve (or table) provided by the calibration laboratory. At any observed force, the best possible accuracy will be obtained by subtracting the corresponding error from the reading. In any test cell which is equipped with a computer-based automatic digital data acquisition system, the error curve should be entered into the software in such a way that the correction is made automatically on every measurement.

7.2 Thrust Simulation

The thrust simulator must produce a controllable, reasonably stable force over the entire range of interest, which for large engine test cells may extend up to 150 000 pounds (667 kilonewtons) or more. Many types of mechanical and hydraulic systems have been used for the purpose, with varying degrees of satisfaction.

The thrust simulator preferably should be equipped with remote controls which permit the operator to adjust the simulated thrust while observing and recording the indications of both the calibration force measurement system and the working thrust measurement system.

Thrust calibration is most easily done if the thrust simulator produces a stable force. In practice most thrust simulators produce forces that change with time. An acceptable drift rate is one that changes less than the allowable measurement error in the time that it takes to read both the thrust calibration indicator and the working thrust indicator.

A data collection system which reads both indicators and calculates the differences automatically can tolerate a greater drift rate than a manual system. Still, an excessively fast drift can produce errors even with an automatic digital data collection system, due to sampling rate effects, non-synchronization of the indicators, varying response time constants of the indicators, minor hysteresis effects, etc. This effect can be eliminated by using identical signal conditioners/indicators that can be externally triggered to take measurement samples simultaneously.

7.3 In-frame Thrust Verification and Calibration

This is the most convenient and generally-used thrust calibration technique because it does not require mounting or removing any equipment. This convenience encourages frequent thrust measurement verification, which is desirable. Users with automatic digital data acquisition systems routinely verify their thrust systems before every engine test to establish a recalibration period.

With in-frame thrust calibration, a range of simulated thrusts is produced by an actuator located on the fixed element of the thrust stand. The force (simulated thrust) is transmitted to the moving element of the thrust stand through the thrust calibration load cell for both increasing and decreasing thrust loads. At each point the measured calibration force is compared to the reading of the working thrust measurement system and recorded. Fully retracting the thrust simulator at the conclusion of the calibration or verification sequence ensures that no calibration forces reach the thrust measurement load cell(s) in normal test operation.

The effect of this calibration is to remove (or greatly reduce) the effects of such thrust stand imperfections as the spring forces of the flexures, the drag of the engine harness, and any systematic errors in the transfer characteristic of the working load cell.

During calibration the zero and span controls (and, in some cases, the curvature control) of the working thrust indicator maybe adjusted to obtain the least possible difference between the readings of the thrust calibrator and the working thrust indicator. If an automatic digital data acquisition system is in use, there may be no separate instrument functioning as a working thrust indicator. In that case calibration consists of adjusting the constants in a thrust conversion table (or algorithm) to bring the error to as close to zero as possible at all calibration points

In either manual or automatic calibration, the procedure is complicated by hysteresis and non-repeatability in the measuring systems. See the discussion in section 7.5 below.

The presence of an engine in the thrust stand may change the behaviour of the thrust stand. In particular, the weight and center of gravity of the engine and adapter may change the at rest position of the moving element of the thrust stand. The engagement of the engine adapter and associated quick connect features can also effect thrust measurement. It must be ensured that the calibration is performed in a representative and repeatable configuration. Therefore, calibration is best done with the engine in place but not running, and with pressure in the fuel supply line (but not in the engine-starting compressed air supply line, because there is no need for starting air once the engine under test is running). If the configuration of pressure lines is controlled (eg. by means of bulkheads and quick connects) and the effect of pressure lines are characterized, quantified and found to be insignificant relative to overall uncertainty, it may not be necessary to pressurize the lines. Some lines (such as hydraulic loading systems) may not be possible to pressurize without operation of the engine.

7.4 Centerline Thrust Calibration

Centerline thrust calibration is a much slower and less convenient calibration method than in-frame thrust calibration, but it is a more accurate simulation of actual engine testing. It is primarily used to develop a centerline thrust correction curve for the in-frame thrust calibration or as an occasional verification of the accuracy of in-frame thrust calibrations in a particular test cell.

In this case, the simulated thrust is delivered to the thrust stand on the engine centerline. A special test fixture is mounted on the thrust stand in place of an engine, and the simulated thrust is transmitted to an attachment point on the test fixture through the centerline thrust calibration measurement system. The attachment point is located at the height of the centerline of engines under test. The simulated thrust may be either a push or a pull along the test cell centerline, depending on the availability of anchoring points in the test cell structure.

The advantage of the centerline thrust calibration method is that the simulated thrust is delivered at the height of an actual engine under test, producing a substantial couple (torque) which loads the thrust stand vertically; while an in-frame simulated thrust does not do so.

Since the centerline technique more nearly simulates the forces produced by an actual engine under test, it is preferred whenever the best possible calibration accuracy is required. If possible, centerline calibration features should be incorporated into a test cell such that performing this operation is efficient. This can include pull arms or attachment fixtures integrated into the test cell structure, and dedicated thrust calibration “dummy” engine & adapters. The “dummy” engine can incorporate features to allow characterization of weight and center of gravity change sensitivity. In this way it is possible to optimize the number of different calibrations that are required for various engines. Note that the test fixture used for centerline thrust calibration should be weighted to approximate the weight and center of gravity of an actual engine.

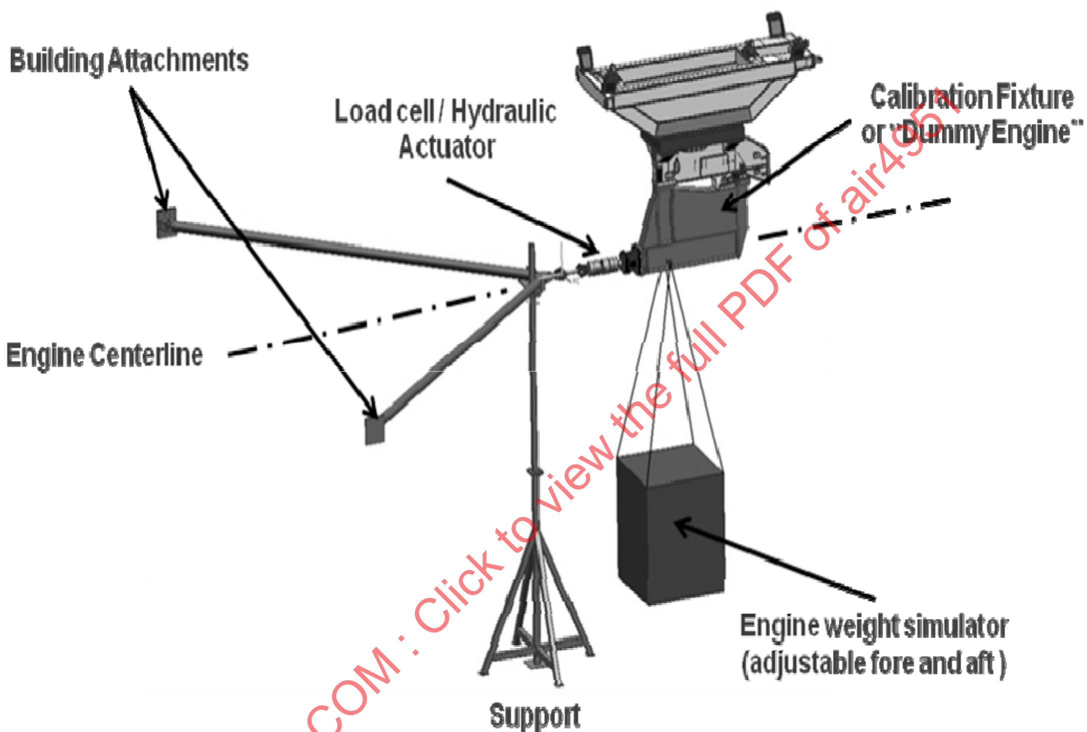

FIGURE 6 - CENTERLINE PULL ARRANGEMENT

The calibration procedures during centerline thrust calibration are essentially the same as those discussed in section 7.3.

7.5 Hysteresis and Non Repeatability

Any force measurement system will have some degree of hysteresis and non-repeatability. In practice, such effects observed during thrust calibration are dominated by the characteristics of the thrust stand flexure plates and the load cells themselves.

It is good practice to cycle the simulated thrust from zero to maximum and back to zero again, twice, before beginning the actual calibration runs. Then one should take an agreed number of points (typically eleven) with increasing force, approximately equally spaced between zero and full scale, followed by the same number of points, less one, with decreasing force. Each pair of readings (one with increasing force, the other with decreasing force) should be taken with approximately the same force, but need not match exactly. The error at each point is the working thrust minus the calibration thrust. The difference between the error observed with increasing force and that observed with decreasing force is a measure of the hysteresis present in the system. A good thrust stand should have hysteresis due to all causes less than 0.1% of full scale at any point. Excessive hysteresis in a thrust stand which formerly behaved well is a warning that something has changed, e.g., damage to a flexure, drag in a safety link, etc.

If the degree of hysteresis is acceptable, it is usual to average the two error values (one for increasing force, the other for decreasing force) to produce the correction which is to be used at that calibration point. In actual engine testing thrust fluctuations can be produced by instability in the intake air flow, variations in the engine control servos (fuel controls), test engine vibrations, adjacent facility vibration, and large-scale turbulence in the engine exhaust. These fluctuations produce minor loops in the system hysteresis which tend to stabilize near the average for increasing and decreasing thrust.

Even load cells of the highest quality will have some degree of non-repeatability; that is, applying identical forces under identical conditions will not produce identical outputs. In addition, minor axial forces produced by the engine services (harnesses and hoses) connected between the fixed and floating frames will vary unpredictably and cannot be fully calibrated out. These effects provide a fundamental limit to the accuracy with which thrust can be measured. The thrust stand designer keeps these effects small by choosing high quality load cells and by keeping the engine services as flexible as possible and consistently configured and attached.

7.6 Thrust Measurement Hierarchy and Recalibration Frequency

The thrust calibration system functions as a secondary standard for force measurement. As such it should be regularly verified by a procedure that is traceable to a primary standard at a national standards laboratory.

The frequency of verification depends on the probable rate of drift of the components of the thrust calibration system, and on the degree of accuracy which it is expected to exhibit. A common practice is to send the thrust calibration transfer standard load cell out for recalibration after six months of service, and if it appears stable to extend the recalibration interval to one year. If the calibration results are trended, the calibration interval for a very stable system may be extended even further.

On the other hand, it is good practice to periodically recalibrate the working thrust measurement system based on trended data. As was noted in section 7.3, some users recalibrate the working thrust measurement system before every engine test. However, it should be recognized that by doing so a real and possibly inconsistent problem (eg. badly installed service link, damaged load cell, etc.) that may have been recognized through trended data could be corrected by a quick in-frame calibration, while it would have been better to identify and correct the problem prior to recalibration.

8. ERROR SOURCES IN THRUST MEASUREMENT

Load cells are a significant source of errors in thrust measurement. Their imperfections include curvature of the transfer characteristic (non-linearity), hysteresis, creep, drift, temperature coefficients, and non-repeatability. Significant errors may also be produced by non-axial forces applied to the load cells (side loading) and by thermal gradients in the load cells. Column type canister load cells are typically more susceptible to side loads than are low profile load cells. The instrument which reads or digitizes the load cell output also contributes various electronic errors, but to a lesser degree.

Unwanted axial forces are produced by the flexure plates (or other means of support of the moving element of the thrust stand), the engine-starting compressed air supply line, the fuel supply line, and various hoses and electrical wires which must connect to the engine under test. Proper thrust calibration procedures permit calibrating out the reproducible portion of these errors, but some random and hysteresis components remain, as well as the fact that not all conditions (including some thermal and transient thermal conditions) can be reproduced during calibration.

In evaluating the thrust measurement system in a test cell, be sure that thrust calibration is done with the engine installed and connected to the test cell systems, that care is taken to avoid side loads on the load cells, and that the load cells are thermally insulated or shielded from the heat of the engine under test. The load cells and their associated electronic instruments should be of adequate quality to give the desired accuracy.

8.1 Classification of Errors

Thrust measurement errors can be classified as systematic or non-systematic. Systematic errors are repeatable and can be corrected with a calibration coefficient. Non-systematic errors are random and cannot be corrected through calibration. In general, changes in the value of systematic errors are proportional to changes in thrust, and changes in non-systematic errors are not proportional to changes in thrust.

The classification of an error as systematic or non-systematic may depend on the measurement objective, which may be repeatability, or absolute accuracy. Most thrust measurement systems are required to act as comparators, comparing the thrust produced by a calibration engine to that produced by the engine under test. Under these conditions, the objective is to design a measuring system with good repeatability. Under other circumstances, such as in development testing, it may not be possible to calibrate the measurement system with a calibration engine. Then absolute accuracy becomes more important.

8.2 Error Sources

Errors in test cell thrust measurement can arise from a variety of sources. For the purposes of these discussions these error sources can be categorized in four distinct areas: 1) Errors inherent in the design of the thrust stand; 2) Errors related to external services connected to the thrust stand; 3) errors related to the thrust stand environment; and 4) instrumentation and acquisition errors.

8.2.1 Errors Inherent in the Thrust Stand

Considerable technology is related to minimizing errors in the basic design of a thrust stand. The challenge is to design a structure to support the test engine in such a way that all the force is applied to the load measuring sensor, and without introducing any additional forces to the same sensor. As discussed in Section 6. above, errors can be related to thrust stand stiffness, gravity effects, friction, alignment and manufacturing tolerance, temperature effects and dynamic response.

8.2.1.1 Stiffness

Errors related to thrust stand stiffness can be separated into the stiffness of the basic structure and the stiffness of the suspension elements.

In conventional thrust stands, thrust force is measured by placing a load cell between a fixed frame and a floating frame. The fixed frame is rigidly mounted, often suspended, from the building structure. The floating frame, which supports the test engine, is freely suspended from the fixed frame, allowing the applied thrust to be transferred to the load cell. The method of suspension must be friction-free, so as not to introduce hysteresis effects in the thrust measurement, and must be significantly flexible to minimize the forces required to deflect the suspension elements. These deflection forces produce a differential between the actual applied thrust and the measured force at the load cell. In an ideal thrust stand, this differential or tare force can be measured during calibration, and factored out in data reduction if it is consistent and repeatable.

However, if the basic thrust stand structure deflects or distorts under load, the thrust stand model is no longer ideal, and flexural deflection forces become less predictable as they vary under differing engine weight and thrust configurations. This renders them incapable of being measured during calibration or factored out in data reduction, and therefore contribute to the increased inaccuracy of the thrust measurement.

Considerable care must be taken in the design and analysis of the basic structure of thrust stand to reduce the effects due to unwanted or unknown deflections. As the engine weight and thrust is applied, the thrust stand deflects and distorts proportional to these loads. These distortions contribute to non-axial loads, side loads or bending loads to the load cell, and increased gravity effects, further discussed below. Each of these effects decrease the measured accuracy of the load cell. Due to internal load cell design these non-axial loads produce friction forces within the moving components of the load cell, or distortion forces between the body and the load sensing element of the load cell. These forces are normally not predictable or repeatable and therefore cannot be factored out as a tare force, and must increase the overall measurement uncertainty of the thrust measurement. The thrust stand design must include basic structure or features to reduce stand deflections to an absolute minimum, and to isolate the load cell to non-axial forces. This is normally done by increasing overall thrust stand structure stiffness and by sometimes using flexible load cell linkage.

8.2.1.2 Gravity Effects

In the conventional thrust stand design the floating frame is suspended from the fixed frame by suspension elements. In a static state these suspension elements hang vertically and the floating frame is at rest in a stable position. However, as the floating frame moves in the direction of thrust, the suspension elements move off vertical much like a pendulum, introducing a gravimetric restoring force as the pendulum tries to return to its vertical at-rest position. This restoring force is in addition to any flexural restoring force of the suspension members. As with the flexural restoring forces, the gravimetric restoring force produce a differential between the actual applied thrust and the measured force at the load cell. Again in the ideal thrust stand model, this tare force can be measured during calibration, and factored out in data reduction if it is consistent and repeatable. However, this force will vary with the mass and center of gravity of the engine/adapter package and will be different for different engine types. Flexure design, including length of flat plate flexure or the use of a fully folded flexure design can mitigate the pendulum effect.

As with the flexural restoring forces discussed above, distortions or deflections in the basic thrust stand structure also cause the gravimetric restoring forces to become less predictable under varying engine weight and thrust conditions. This increases the overall inaccuracy of the thrust measurement.

As noted above, many thrust stands suspend the floating frame below the fixed frame by the suspension elements, and the floating frame acts as a pendulum. Some thrust stands have the floating frame supported above the fixed frame on the flexural elements. In this case an "inverted pendulum" effect occurs, where the pendulum does not act with a restoring force but with an additive force.

8.2.1.3 Friction

Friction between moving parts of the thrust stand is the single largest contributor to hysteresis and repeatability errors in the thrust measurement. Frictionless joints are especially critical in the suspension elements, the load cell linkage, and internal to the load cell. Ball-and-socket, clevis-and-pin, and other similar joints should be avoided in favor of flexure pivots for suspension elements and load cell linkage. In compression load cell applications, lateral displacement of the floating frame from the fixed frame can cause hysteresis due to the friction between the load cell "button" and the floating frame. If the friction is great the displacement will introduce a side load on the load cell button without slipping. However, as is almost always the case, the differential movement causes a side load on the load cell until the friction force is overcome and the floating frame slides sideways on the button. As the differential movement returns to normal the floating frame slides back again to a more normal position. Unfortunately, the nature of this arrangement makes this side load/sliding action occur unpredictably with each up-down cycle of thrust load, increasing thrust measurement inaccuracy. In tension and compression systems, the load cell can be attached by means of links between the fixed and floating frames so while there can still be an applied side load the non-repeatability due to sliding is avoided. These links may include threaded rods with optional universal flexures at the attachment points.

Internal load cell friction is a function of the design of the load cell, and is manifest in the published side load and bending inaccuracy figures. The good thrust stand design will minimize applying any side or bending loads to the load cell by a design which minimizes deflections or distortions in the thrust stand structure.

8.2.1.4 Alignment and Manufacturing Tolerance

Alignment and manufacturing tolerance of the thrust stand components can affect thrust measurement accuracy. If the thrust stand components are poorly aligned or vary in dimension due to manufacturing tolerance, the thrust stand can assume an asymmetry which leads to thrust reading error. Examples could include a load cell not aligned parallel to the line of thrust, unequal length flexure elements, unequal lengths between fore and aft flexures, etc. Off axis loads result in side loads being applied to the load cell, the effect of which can be reduced by the use of a universal flexure. Additionally, thrust stand elements must be positively retained in position to avoid inaccuracy. A joint which shifts between calibration and operation, or shifts during or between engine tests can be a major source of inaccuracy, and often difficult to identify. Care must be taken in the design to select appropriate tolerances, alignment methods, retention methods, and manufacturing quality to reduce thrust measurement uncertainty.