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(R) Test Cell Instrumentation

RATIONALE

AIR5026 is being revised per the five year re-affirmation requirement. This revision will update the document to reflect test cell instrumentation and hardware currently in use and available for use in post-overhaul gas turbine engine testing. Some of the advances in measurement systems and hardware are included in this update.

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1. SCOPE

1.1   General

This document discusses, in broad general terms, typical present instrumentation practice for post-overhaul gas turbine engine testing. Production engine testing and engine development work are outside the scope of this document as they will typically use many more channels of instrumentation, and in most cases will have requirements for measurements that are never made in post-overhaul testing, such as fan airflow measurements, or strain measurements on compressor blades.

The specifications for each parameter to be measured, in terms of measurement range and measurement accuracy, are established by the engine manufacturers. Each test cell instrument system should meet or exceed those requirements. Furthermore, each instrument system should be recalibrated regularly, to ensure that it is still performing correctly.

1.2   Engine Performance

The basic output of a turbofan or turbojet engine is the thrust produced by the engine. Some industrial gas turbine engines are tested without their power turbines installed, and in consequence are also characterized by thrust. Other engines use engine pressure ratio, EPR, instead of thrust to determine performance. EPR performance testing requires the use of a standardized air-intake bellmouth and standardized exhaust tailpipe so that the relationship between thrust and EPR is reproducible.

Gas turbine engines which primarily drive output shafts: turboshaft, turboprop, industrial, and marine engines, are characterized by output shaft speed and torque, and therefore output power.

A few relatively small turbofan engines deliver enough power to various accessories, such as electrical generators and hydraulic pumps, so that known loads must be applied to their accessory shafts when the engine thrust is being measured. For most engines, however, the effect of accessory loads is negligibly small, and the accessory shafts need not be loaded. Back-to back correlations between engine manufacturer's test facilities and other test facilities are typically done without any engine accessory pad loading.

Many aircraft-type gas turbine engines can furnish substantial amounts of compressed air, called bleed air, taken from one or more stages of the intake air compressor. This compressed air is used to start other engines, to drive cabin air conditioning, etc. In ordinary post-overhaul testing the engine performance is measured with no bleed air flowing. Many engines have valves which bleed off controlled amounts of compressed air under certain conditions; that air is simply wasted. Those functions are allowed to proceed normally during post-overhaul testing.

Auxiliary power units, APUs, and ground power units, GPUs, deliver most of their output energy in the form of compressed air, and a smaller amount of energy as a shaft drive for an electrical generator. Both the compressed air flow and the generator shaft output power must be controlled and measured when testing these engines.

1.3   Beneficiaries

The information contained in this document will benefit anyone who is preparing to build and equip a test facility for any type of gas turbine engine, or to contract with a specialist to do such work.

2. REFERENCES

2.1 Applicable Documents

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
ARP4990	Turbine Flowmeter Fuel Flow Calculations
ARP6068	Gas Turbine Engine Test Facility Vibration Measurement
AIR4869A	Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cells
AIR4989	Design Considerations for Enclosed Turboshaft Engine Test Cells
AIR5295	Design Considerations for Enclosed Turboprop Engine Test Cells
ARP4755A	Turboshaft/Turboprop Gas Turbine Engine Test Cell Correlation
ARP5435	APU Gas Turbine Engine Test Cell Correlation
ARP5758	Trend Analysis for Maintaining Correlation of Gas Turbine Engine Test Cells
AIR4827A	Modeling Techniques for Jet Engine Test Cell Aerodynamics
AIR4951	Test Cell Thrust Measurement

2.1.2 Other Publications

"Measurement Uncertainty: Methods and Applications", 4th Edition, Dieck, Ronald H.; ISA – The International Society of Automation, 2007, ISBN-13: 978-55617-915-0.

"Report 530, Properties of Aircraft Fuels", Coordinating Research Council, Atlanta, Georgia, 1983.

2.2 Definitions

The following list defines certain terms and phrases used in this document:

ACCURACY: This is properly defined as the closeness or agreement between a measured value and the true value, so that a 99% accurate reading has a 1% error. However, almost all vendors of instrumentation have adopted the practice of identifying the instrument accuracy by stating it's probably inaccuracy, in some form such as ±0.5% of full scale value, or ±2% of reading over the range from 10 to 50 psig. This paper also follows that practice. Note that it is improper to specify an inaccuracy of a fixed percentage of reading without some lower limit; if the range is allowed to go to zero, the allowable error also goes to zero, an unattainable objective. For those cases in which a more detailed analysis of sources of error (bias error, precision error, etc.) is required, see the full treatment in reference document 2.1a.

ALIASING: A phenomenon of sampled signals in which the data is distorted due to an insufficient sampling rate. Nyquist's theorem states that a waveform must be sampled at a rate of at least two times its highest frequency component in order to prevent aliasing of the original waveform.

ANALOG: A variable quantity or instrument for measuring it, which varies continuously over some defined operating range. Reading an analog instrument requires the user to observe the position of a pointer moving over a calibrated scale, or the height of a fluid on a scale, etc., in making the measurement.

AUXILIARY POWER UNIT (APU): This is a gas turbine engine, mounted in an aircraft, which is designed to produce compressed air for such functions as cabin air conditioning or starting other engines, and to drive an electrical generator. Some APUs are used only when the aircraft is on the ground and are shut off when the aircraft's main engines have been started. Others may be used in flight as well.

BYPASS AIR: In a turbofan engine, air which the engine draws in and does not pass through the engine core. It is compressed slightly and discharged together with the core engine exhaust.

BYPASS RATIO: In a turbofan engine, the mass flowrate of bypass air divided by the engine core flow mass.

COMPRESSOR STALL: A condition in which one or more blades in the engine compressor cannot maintain the pressure differential across them. It is related to the "stall" of an aircraft wing; the compressor blades are airfoils, and flow separation produces a stall. If a stall propagates through the whole compressor, violently interrupting the proper functioning of the engine, the event is called a surge.

CORE AIRFLOW: Air that a gas turbine engine draws in that passes through the engine core or power section as part of the combustion process.

DIGITAL: A variable quantity or instrument for measuring it, which is represented by discrete, usually numerical, values. A typical digital instrument will display a measurement in such a form as 123.14.

GROUND POWER UNIT (GPU): This is a gas turbine engine, similar in function to an auxiliary power unit, but which is mounted on a cart or truck and is brought to the aircraft which it is to serve on the ground.

INDUSTRIAL ENGINE: This is a turboshaft engine which is designed for nonaircraft applications, such as electrical generation, driving petroleum pumps, etc. Industrial engines can be much heavier, and therefore more rugged, than comparable aircraft engines. Some industrial engines are designated as marine engines.

K-FACTOR: In a turbine or vortex flowmeter, the number of electrical impulses it delivers per unit volume of the fluid being measured. It is often treated as approximately constant over some useful range of fluid flow rates.

MARINE ENGINE: An industrial engine which is designed for marine service, such as driving a ship's propeller.

REHEAT ENGINES: Also called afterburning engines, these are turbojet or turbofan engines in which additional fuel is injected into the airflow, either bypass air or the exhaust air from the main combustion process, and burned there to raise the air temperature, the airflow volumetric flow rate, and therefore the engine thrust.

RESISTANCE TEMPERATURE DETECTOR (RTD): A temperature-sensing device which consists of an electrical resistor that has a known characteristic of resistance versus temperature. RTDs are made of lengths of wire or thin films of metal deposited on an insulating substrate, and typically have resistances in the order of hundreds or thousands of ohms. See thermistor.

RESOLUTION: The smallest observable increment in the variable being measured by the instrument, usually stated as a fraction of full scale.

THERMISTOR: This is an RTD made of a semiconducting material. Thermistors are available with very large, either positive or negative, temperature coefficients of resistance. Their stability and reproducibility are usually not adequate for accurate temperature measurement, but thermistors are often used in control systems.

THERMOCOUPLE: A temperature-sensing device which consists of two conductors of dissimilar electrothermal characteristics. The conductors are joined together at one end, the hot junction, where the junction is placed in contact with the item whose temperature is to be measured. At the other end, the cold junction, a voltmeter or other device is used to measure the electrical voltage which is produced by the difference in temperature between the two junctions.

TIME AVERAGE MEAN: An averaging method in which test data is recorded at a constant rate over a predetermined period of time and then averaged. This method is used to minimize the impact of data scatter due to steady state engine fluctuations.

TRIBOELECTRICAL: The separation of electrical charges of opposite sign by processes such as friction between two solid bodies.

TURBOFAN ENGINE: A gas turbine engine which draws in more air than the combustion process requires, compresses the bypass air slightly, and discharges it together with the core engine exhaust. The earliest turbofan engines had bypass ratios of 1.0 or less; the largest current turbofan engines have bypass ratios up to 11:1.

TURBOJET ENGINE: A gas turbine engine which is designed to power an aircraft by drawing in air, compressing the air, burning fuel to heat the air, and discharging the hot compressed air in such a way as to produce the thrust which moves the aircraft. A turbine in the exhaust stream extracts enough energy from it to drive the intake air compressor. See turbofan engine and reheat engine.

TURBOPROP ENGINE: A turboshaft engine which is designed to drive an aircraft propeller.

TURBOSHAFT ENGINE: A gas turbine engine which primarily delivers its output power to turn an output shaft. A typical application is to drive a helicopter rotor. See turboprop engine and industrial engine for specialized forms of turboshaft engines.

UNCERTAINITY: The margin of error or amount of random sampling error of a measurement.

3.   INSTRUMENT CHARACTERISTICS

3.1   Analog versus Digital Instruments

In the early days of gas turbine engine testing, most measurement instruments were analog devices: liquid manometers, Bourdon-tube pressure gauges, d'Arsonval electrical meters, etc. Over the years, the use of digital instruments has become prevalent in gas turbine testing.

Digital instruments can have both higher resolution and better accuracy than comparable analog instruments. They also avoid several common sources of errors such as: counting calibration marks between numbered points, interpolating between calibration marks, and parallax offsets between the needle and the instrument scale.

On the other hand, analog instruments are much easier to read than digital instruments when the parameter being read is changing rapidly. For example, small fluctuations of an otherwise stable pressure may make the needle of a Bourdon-tube pressure gauge flicker back and forth over a well-defined band; it is relatively easy to look at the instrument, estimate the center of the band, and report that as the reading. Experienced operators doing this hardly realize that they are performing an averaging function.

The same parameter, read on a digital instrument, is harder to deal with. If the instrument updates rapidly, the least significant digit may be a blur of superimposed figures. If the update rate is only a few times per second, the operator can distinguish each successive reading, but the values are likely to jump around randomly. About all he can do is to watch for a period of time, observe the highest and lowest values, and report their average as the reading.

The best solution is to use a digital instrument, because of its higher accuracy, but to slow down the rate of response of its analog circuitry by means of a low-pass filter so that it does most of the averaging for the operator. Such a filter also discriminates against much of the electrical noise, and has anti-aliasing properties.

Unfortunately, some gas turbine engine parameters inherently fluctuate so much that an instrument which has adequate filtering (i.e. a long time constant) may respond too slowly during starting, slam accelerations, and other transient situations. Some specialized digital instruments have variable filtering, which can be switched from one mode to another as needed. This is readily done in computer-based systems with digital filtering techniques.

In some engine-testing situations a critical parameter (say, EGT - exhaust gas temperature) may be increasing rapidly, and the operator must decide quickly whether it will settle at a safe value or whether he should shut the engine down. The judgment is much easier with an analog indicator than with a digital one. For that reason, in many computer-based systems critical parameters are displayed in quasi-analog form in addition to the digital display. One example would be a bar graph which uses unfiltered data for fast response.

Digital data can also be displayed with excessive precision lending significance to meaningless digits. The number of significant digits displayed or recorded should take into account the accuracy of the instrumentation being used to measure the data.

3.2   Steady State Measurements

A typical set of data for an engine performance point is taken only after the engine has been allowed to stabilize at the desired power level for a few minutes. For such measurements, the normal fluctuations which occur in many engine parameters are only a nuisance; what is desired is an average value. If the test cell is equipped with a computer-based data acquisition system, it may be allowed to record each parameter for a period of time, perhaps a few tens of a second or more and calculate an average. This method is referred to as Time Average Mean. If there is no computer, the test cell operator must estimate an average value for each fluctuating parameter. Typically, the operator will note the highest and lowest readings in a suitable period and will calculate their mean value.

3.3   Transient Measurements

Measurement of an engines transient response to a dynamic input such as a commanded acceleration, deceleration, or rotating inlet distortion screen requires the use of instrumentation with a high response rate. Vibration measurements during engine acceleration can provide data which can be used to determine bearing conditions and rotor balance issues.

Nonuniformity of the air flow at the engine's air intake makes the engine less stable. Very poor intake air flow can even cause the engine to stall or surge. The degree of fluctuation in such parameters as rotor speeds and engine thrust can give a useful indication of the intake air flow quality. Note that even with ideally perfect intake air flow some residual fluctuations will be produced by instabilities in the engine's fuel control servo and by large scale turbulence in its internal air flows. The observed fluctuations will be affected by the dynamic characteristics of the instrumentation systems.

Measurements of the fluctuations of rotor speeds and thrust in different test cells are not comparable unless the measuring instruments in the two cells have equivalent rates of response to changes, or both instruments have rates of response much higher than the engine fluctuation rates.

4.   THRUST MEASUREMENT

4.1   General

Although test cells may be encountered occasionally which use mechanical weighing systems or hydraulic load cells to measure thrust forces, the greater accuracy and convenience of electrical strain gauge load cells have made them a generally-used standard for many years. Test cell thrust measurement is discussed in depth in reference document 2.1m, from which most of the following material is extracted.

The mechanical design of the thrust stand may require that the engine thrust be measured with load cells of various configurations such as a single load cell in tension, a single load cell in compression, or a pair of load cells in compression or tension. This discussion neglects the special requirements of multi-axis thrust stands, which are outside its scope.

4.2   Uncertainty in Thrust Measurement

With well-designed thrust stands, the load cells are the principal source of the uncertainty in thrust measurement. Their imperfections include curvature of the transfer characteristic, hysteresis, drift, creep, temperature coefficients, and non-reproducibility.

Serious errors in thrust measurement may be produced by side loading of the load cell. Side loading maybe caused by non-axial forces or by thermal gradients in load cells exposed to wide temperature variations, especially in winter. The instrument which reads the load cell output also may contribute various electronic errors.

Unwanted axial forces are produced by the flexure plates or other means of support of the moving element of the thrust stand, the starting air supply line, the fuel supply line, and the various hoses and electrical wires which must connect to the engine under test, often referred to as the engine harness. Proper thrust calibration procedures permit calibrating out the reproducible portion of these errors, but some random and hysteresis components remain. Careless engine dress, that is, placement of the harness, has often produced significant thrust measurement errors.

In evaluating the thrust measurement system in a test cell, be sure that the centerline thrust calibration is done: 1) with the engine installed and connected to the test cell systems; or 2) with a rigid structure providing the correct centerline pull location.

Care should be 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.

It is important to recognize that the instantaneous thrust of an engine is not constant; large-scale turbulence in the exhaust stream produces small rapid variations in thrust. In spite of the inertia of the engine and its support structure, a significant amount of these fast fluctuations reaches the thrust measuring system, and causes instability of the thrust reading.

Any digital thrust measuring system should have an input low-pass anti-aliasing filter to minimize the disturbance of its reading by exhaust turbulence effects. With a sampling rate of N readings per second, the anti-aliasing filter should have greater than 20 dB of attenuation from N/2 Hz on up, with at least 40 dB of attenuation at 10 Hz.

4.3   Thrust Calibration

Most modern thrust stand designs include provisions for application of a simulated thrust to the thrust stand through a calibration load cell. The thrust simulator, typically a hydraulic cylinder, and the calibration load cell are mounted within the thrust frame, and the simulated thrust is applied at or near to the elevation of the working load cell or cells. With this scheme a calibration of the working thrust measurement system can be done in a few minutes, so quickly that many operators verify one or two calibration points before every engine test.

On the other hand, such a thrust calibration system does not stress the thrust stand in the same way as the actual engine thrust. The engine must be offset from the thrust frame structure in order to allow unobstructed entrance of air and exit of exhaust gases. Therefore a method of thrust calibration which applies the simulated thrust at the engine centerline is a better technique. Mounting a simulated engine or rigid structure and connecting a force loading system at the level of the engine centerline is relatively time-consuming task. Test facilities typically have a master load cell that has been verified against a lab standard as part of the force loading system. How often an engine centerline is completed is determined by the test cell owner.

Most operators simply use in-frame thrust calibration, assuming that the thrust stand design is such that the difference between in-frame calibration and centerline calibration will be negligible. It is good practice to make a centerline thrust calibration cross-check on any new thrust stand, and occasional conduct a cross-check test of existing thrust stands to make sure that the characteristics of the thrust stand has not changed. A centerline calibration should be completed whenever any modifications are done to the test stand that may affect thrust measurement.

The centerline master calibration load cell and its associated thrust indicator serve as the primary standard. The in-frame calibration load cell and its associated thrust indicator serve as a secondary standard. Both systems should be sent out periodically to a standards laboratory which can calibrate them against standards that are traceable to a national standard.

5.   TORQUE MEASUREMENT

5.1   General

Typical turboshaft, turboprop, industrial, and marine engines are loaded for test by propellers, dynamometers of various types, and water brakes. The useful power output of the engine under test is the product of the output shaft speed and its torque. Best practice is to equip the test facility with accurate torque measurement instrumentation which can be sent out for calibration traceable to a national laboratory standard.

5.2   Shaft Rotary Torque Measurement

The most accurate commercial torque measuring instruments use strain gauges mounted or bonded on the rotating shaft to measure the engine torque which the shaft is transmitting. The strain gauges deform when a torque is applied which causes a change in electrical resistance. A Wheatstone bridge converts the resistance change into a calibrated output signal. There are three general techniques for making electrical connections from the rotating strain gauges to the test cell wiring: slip-rings; a specialized transformer which has a secondary that rotates with the shaft; and a radio-frequency data link. Each technique has advantages and disadvantages, and the optimum choice depends on such variables as the maximum shaft speed, ambient temperature, sampling rate, and the desired operational life of the instrument.

Rotary shaft torque sensors can be integral to the shaft, mounted between shaft sections, mounted between flanges, or clamped-on the shaft. The clamp-on sensor uses pre-calibrated bending beams mounted between two collars to measure shaft torque.

5.3   Reaction Torque Measurement

If the loading device is a dynamometer, its outer case or housing carries the engine's output torque, and transmits it to the test bed support frame. One common technique is to mount the dynamometer on bearings so arranged that it will turn freely in the direction of shaft rotation. Then a lever attached to the case of the dynamometer is arranged to bear on a load cell, similar to those used in thrust measurement (see Section 4) preventing it from turning. If the load cell is at a known radius from the shaft centerline, the product of that radius and the force measured by the load cell is the torque being absorbed by the loading device.

An alternate technique is to support the dynamometer by a structure which is concentric with the engine shaft, and which is fitted with strain gauges that measure the torque required to restrain the dynamometer case. Often the reaction torque support structure is a hollow cylinder, large enough in diameter so that the engine shaft can pass through it.

In a reaction torque measurement scheme it is important to minimize any external torques applied to the dynamometer case, such as torques caused by hoses bringing water to and from a water brake. Any such connections should be made close to the shaft centerline, to reduce the torque produced by a given force.

In a few instances, reaction torque has been measured by permitting the engine, rather than the dynamometer, to rotate. The torque produced by some propeller-loaded engines was successfully measured in this way. There are many difficulties with this technique, which is not generally used.

5.4   Torque Calibration

Calibration of a torque measurement system requires applying a series of known torques and observing the instrument readings. This is most simply done by attaching a calibration arm of known length to the engine shaft or to the dynamometer, leveling the arm accurately, and loading it with a set of accurately-known weights.

The instruments used in torque measurement are subject to the same kinds of errors as those used in thrust measurement (see Section 4.2) but in this case they are less troublesome. That is because the engine manufacturers typically have tolerated larger errors in torque measurement than in thrust measurement.

6.   FUEL FLOW MEASUREMENT

6.1   General

Engine fuel flow requirements are typically specified in mass flow terms. There are currently two different types of fuel flow measurement devices in use. Some types measure mass flow directly such as a Coriolis flowmeter. Others measure in volumetric flow such as a turbine flowmeter, positive displacement flowmeter, and vortex shedding flowmeter. Converting the output of any volumetric device to mass flow requires knowledge of the density or specific gravity of the fuel.

The requirement for accuracy of fuel flow measurement has increased as the cost of fuel has escalated, and as engine manufacturers have given increasingly stringent fuel efficiency warranties to their customers.

6.2   Turbine Flowmeters

Most test facilities currently measure fuel flow by means of a turbine flowmeter. For transient testing, the turbine flowmeter produces the best results among available flow measurement devices.

The output from a turbine flowmeter is a frequency signal. One electrical impulse as each turbine blade passes a pickup, sometimes called a pickoff, which typically is measured by an electronic counter with a variable time base. The volumetric output from the turbine flowmeter is converted to mass flow by one of two methods. The recommended method is to use the Rushko Strouhal curves from the flowmeter calibration to convert the flowmeter frequency reading to a mass flow. The second method is to use the flowmeters K-factor, given in counts per unit volume, and the known fuel density, to calculate mass flow. The advantage of the Roshko Strouhal method versus K-factor/fuel density method is that it takes into account temperature effects on the flowmeter unit. For a detailed analysis on the use of turbine flowmeters refer to reference document 2.1d.

Turbine flowmeters have rated accuracies from 0.1 to 0.5% of reading, over a restricted range of flow rates, typically from full-scale down to about 10% of full-scale. The ratio of full-scale flow to the lowest flow at which the meter will meet its accuracy specification is called its turn-down ratio or range. With a given design of turbine flowmeter, an inexpensive magnetic pickup will produce a small drag on the turbine and will reduce the turn-down ratio; the radio-frequency pickup causes little or no drag and gives the best possible performance. A few flowmeters have turn-down ratios of 100:1 or more, using special linearization techniques.

To obtain full rated accuracy, long straight runs of pipe, or shorter runs containing flow straighteners, must be used both upstream and downstream of any turbine-type flowmeter. The minimum suggested inlet and outlet lengths are ten and five pipe diameters, respectively.

A counter of good quality will contribute only negligible error to the measurement. Frequency measurement techniques are discussed in some detail in Section 8 of this document.

A manufacturer's turbine flowmeter stated accuracy assumes a measurement period that corresponds too many turns of the turbine rotor. A few users who wish to measure transient fuel flow rates, and therefore choose very short measurement periods, have encountered errors due to nonuniformity in the blade-to-blade spacing of the turbine blades. Such errors can be avoided by measuring the fuel flow for an integral number of turns of the turbine; for example, if the turbine has eight blades, a measurement of the time for 8, 16, etc. blades to pass the pickup will not be affected by any nonuniformity in the turbine blade spacing.

Other than catastrophic failures, turbine flowmeters typically degrade gradually as their bearings wear.

6.3   Viscosity Effects

Changes in fuel viscosity will affect a turbine-type flowmeter's turn-down rating. In general, as the fuel's viscosity increases the flowmeter's departure from linearity in the low-flow region increases. Changing fuel temperature from a typical summer temperature of 86 °F (30 °C) to a winter temperature of 0 °F (-18 °C) will approximately double the fuel viscosity, halving the flowmeter's turn-down rating. Much of this viscosity effect can be counteracted, if the viscosity is known, by presenting the meter calibration in the form of a universal viscosity curve, a widely-used tool. In it, the flowmeter K-factor is plotted against the meter frequency in Hz divided by the fluid's kinematic viscosity in centistokes. Knowing the viscosity and the observed meter frequency, the appropriate K-factor can be chosen from the universal viscosity curve and used to calculate the flow rate. Common practice is to have each batch of fuel analyzed by the supplier to obtain a minimum of two viscosities values at widely-spaced temperatures. Viscosities at other working temperatures can then be determined. Refer to reference document 2.1d for a detailed discussion on this topic. Although the universal viscosity curve is only an approximation to the actual behavior of a turbine meter its use is strongly recommended in order to extend the useful range of a turbine flowmeter.

6.4   Temperature Effects

Changes in fuel temperature, and therefore of the flowmeter temperature, primarily affect the fuel density and viscosity. In addition there is a small thermal effect because of dimensional changes in the flowmeter itself; this is normally neglected in post-overhaul engine testing, but should be included in very precise measurements. Using the Roshko Strouhal method will account for the dimensional changes.

6.5   Flowmeter Verification

Flowmeter verification is completed using a calibration process to ensure that the flowmeter meets specifications.   Most users periodically send their flowmeters to a laboratory which can calibrate them using instrumentation that is traceable to a national standard. Some users maintain a master flowmeter, which has been calibrated at a standards laboratory and is used infrequently, for comparison with their working flowmeters. Verification of a flowmeter is seldom possible in the field, except by comparison with another flowmeter connected in series with it.

6.6   Fuel Density Measurement

Errors in measurement of fuel density or specific gravity are of first-order importance in calculating gravimetric fuel flow. Ideally, fuel density should be measured continuously by a densitometer, and its reading should then be used to convert the flowmeter's volumetric data to gravimetric form.

In many cases a fuel sample is drawn before the engine test begins, and its measured density is used thereafter to calculate the gravimetric fuel flow. In that case, the working fuel temperature should be measured continuously, and a table or curve of fuel density versus temperature, such as those contained in reference document 2.1b, should be used to estimate the current fuel density. If no such correction were made, and if the actual working fuel temperature were, say, 10 °F different from the temperature of the density sample, the calculated gravimetric fuel flow would be in error by about 0.5%.

6.7   Vortex Flowmeters

Vortex flowmeters are based on the Von Karman Vortex Street principal. A bluff object usually a bar in placed in the center of a circular tube and the frequency of the alternating vortices coming off the back of the object is proportional to the volumetric flowrate. A frequency pickup located behind the object picks up the pulses in the flow.

6.8   Mass Flowmeters

Mass flowmeters typically are based on the Coriolis Effect. Fuel flowing through a vibrating tube causes a measurable twisting motion in the tube which is directly proportional to mass flow. Commercial mass flowmeters currently have accuracy ratings of 0.1% of reading and turn-down ratios from 100:1. Mass flowmeters do not require density corrections, or temperature corrections, and are not affected by fuel viscosity changes. Mass flowmeters have a high degree of safety and reliability, do not require straight sections of inlet or outlet piping, and minimal regular maintenance is required.

6.8.1   Mass Flowmeter Installation Effects

Manufacturer installation requirements must be followed in order to avoid outside vibration affecting the meter readings. Meters should be located and secured in a location unlikely to be affected by vibration or noise. When installing a Coriolis type flowmeter to measure liquids, the meter should be positioned below the centerline of the engine in the correct fluid orientation to prevent air from being trapped in the meter. Mount the meter such that there is unlikely to be any undue stress or twist when connecting to the supporting pipe work.

6.9   Positive-Displacement Flowmeters

These volumetric meters were originally developed to measure deliveries of fuel, typically from tank trucks refueling aircraft. Their designs were optimized for accuracy in measuring total fuel delivered over a relatively small range of flow rates. Such flowmeters are used in some test cells to record the total fuel consumed in the course of each engine test, particularly in circumstances where fuel costs are billed to a customer. In some instances positive-displacement flowmeters have been modified in ways that permit them to be used for rate-of-flow measurements in engine test cells. They are not well suited for situations in which the fuel flow rate must be sampled frequently. Uncertainty ratings of 0.25% of reading are typical for steady state testing.

7.   TEMPERATURE MEASUREMENT

7.1   General

In order to understand the performance of a gas turbine engine, it is necessary to measure gas temperatures at many points within the engine. The temperatures to be measured range from that of ambient air, which may be as low as -40 °C (-40 °F) under arctic conditions, to that of burning fuel, which may be as high as 2000 °C (3632 °F).

7.2   Thermocouples

Most engine-related temperatures will be measured with thermocouples, usually types E, J, K, N, or T. Thermocouple manufacturers control the composition of the metal alloys which make up their thermocouples to assure that the relationship between temperature and output voltage is consistent. Standard thermocouples meet the NIST tables of temperature versus output electromotive force (EMF) within the tolerances shown in Table 1 at temperatures above 0 °C. Premium thermocouples have errors about half as large.

Although electrical instruments are readily available which will read the weak electrical signals from thermocouples with an accuracy of a few tens of microvolts, corresponding to an error of about 0.5 °C, the variability of individual thermocouples is much greater, as shown in Table 1. Therefore the thermocouple error limits the system accuracy.

TABLE 1 – STANDARD THERMOCOUPLE TOLERANCE LIMITS

Thermocouple	Tolerance (whichever is greater)
E	1.7 °C or 0.5% of reading
J	2.2 °C or 0.75% of reading
K	2.2 °C or 0.75% of reading
N	2.2 °C or 0.75% of reading
T	1.0 °C or 0.75% of reading

7.2.1   Thermocouple Extension Wire

The above errors apply when the thermocouple leads are connected directly to a measuring instrument, with a cold junction held at 0 °C. That is typically not possible in a test cell, hence extension wires are used. The extension wires must be of the same type as the thermocouple. Extension wires of standard quality will contribute errors of the same size as those listed above for the basic thermocouples. Extension wires of premium quality have approximately half the errors shown in Table 1.

It is very important that all thermocouple circuits in a test cell have extension wires of the proper type, preferably of premium quality, and that they be connected correctly: iron to iron, constantan to constantan, etc. Improper extension wire types and connection reversals can produce large temperature-dependent errors; such systems may calibrate correctly with no engine running, yet may have serious errors when a running engine heats the thermocouple-to-extension-wire junctions.

Any nonthermocouple materials in connectors, terminal blocks, etc. will add further errors in any case where there are significant thermal gradients. For example, consider a connector pair with copper pins, and a chromel wire, part of a type K thermocouple system, connected to each of the mating pins. There will be a thermal EMF produced between the chromel wire and the male pin, and another one between the female pin and its chromel wire. If the temperatures of the two junctions are equal, the two thermal EMFs will balance out. But any temperature difference between the two will produce a net spurious EMF which will cause an error in the system's temperature measurement.

7.2.2   Reference or Cold Junctions

Most thermocouple systems now use cold junctions which are not held at a fixed temperature. Instead, the cold junction block has heavy thermal insulation, so that its temperature changes slowly and is nearly uniform from end to end. The cold junction temperature is measured, usually with an RTD, and supplied as an electrical signal to the temperature indicator, which uses that information to correct its display to what it would have been with a cold junction temperature held at 0 °C. Both the indicator and the cold junction system contribute small errors to the temperature measurement.

7.2.3   Paralleling Thermocouple Instruments

Most modern thermocouple indicators draw such a small amount of current from the thermocouple system that the voltage loss through the resistance of the thermocouple wiring, often called IR drop, can be neglected, and instruments can be paralleled freely.

When two or more thermocouple indicators are connected in parallel to read the same temperature, open-thermocouple detector circuits may cause trouble. Many open-thermocouple detectors apply a periodic pulse of current to the thermocouple. If one indicator is measuring the temperature while the other is applying such a pulse, its temperature reading will be disturbed.

7.2.4   Thermocouple Troubleshooting

Troubleshooting of individual thermocouples is usually limited to comparing a questionable thermocouple to a known good one. If a thermocouple is producing incorrect readings, it is discarded and replaced with a new one.

There are many possible causes of incorrect thermocouple readings. A thermocouple may give incorrect readings because of heat conducted through its leads or its mounting, radiation effects, and other environmental problems. In addition, thermocouples exposed to high temperatures, such as those used for measuring EGT of a gas turbine engine, tend to drift, that is, to change characteristics with time, due to development of inhomogeneities in the wire in regions of high temperature gradient. Corrosion of thermocouple wires and connectors can be a serious problem, especially in the case of the iron lead of the common type J thermocouple.

It is desirable to check the wiring and the measuring instrument of a thermocouple system regularly. A source of simulated thermocouple voltage is connected in place of the working thermocouple. The voltage source usually is calibrated in equivalent temperature for a particular thermocouple type. The reading of the working instrument is compared with that of the voltage source. Disagreements between the two readings may be caused by wiring errors, stray thermoelectric voltages, and instrument errors.

7.3   Resistance Temperature Detectors

Engine inlet air temperature should be measured accurately, because of the sensitivity of engine performance to inlet air density. Although most test cells still use thermocouples to measure inlet air temperature, the greater stability and accuracy of platinum resistance temperature detectors (RTDs) makes their use preferable.

RTDs are also called resistance temperature bulbs (RTBs). They may be made with wires of platinum, nickel, copper, or other metals, or thin films of metal on an insulator. The platinum RTD is generally accepted as the most stable and reliable. The rate of change of resistance with temperature of a 100 Ω platinum RTD is less than 0.4 Ω/°C, so that 4-wire measurement techniques are required in order to eliminate errors due to ambient temperature effects on the resistance of the wires leading to the RTD from the control room.

Two different platinum alloys are widely used for RTDs; one type has a thermal coefficient of resistance of 0.00385 Ω/Ω/°C, and is primarily used in Europe; the other has a coefficient of 0.00392 Ω/Ω/°C, and is primarily used in the U.S.A. Other alloys are used occasionally, with coefficients ranging from 0.00375 to 0.00393.

With a suitable signal conditioner and indicator, a high quality platinum RTD will have a working error less than $\pm$0.5 °C over the ambient temperature range. Better accuracy can be obtained by means of careful calibration of an individual RTD together with its associated signal conditioner.

7.3.1   Calibration of Resistance Temperature Detectors

Good-quality platinum RTDs are very stable over long periods of time, and should not need recalibration unless they experience physical damage. The instrument which reads the resistance is much less stable, and should be checked periodically by connecting it to accurately known resistors.

Occasionally it is desired to make temperature measurements with accuracy greater than the standard rating of an RTD as supplied from the factory. In that case the RTD to be calibrated must be immersed in a constant-temperature, well-stirred liquid bath. The bath temperature must be known accurately. Laboratory mercury-in-glass thermometers are available with limited temperature ranges and with calibration markings at intervals of 0.1 degree so that the bath temperature can readily be observed to 0.05 degree. The RTD and its associated instrument or signal conditioner must be calibrated together. This type of calibration, while simple in concept, is relatively difficult in practice.

7.4   Thermistors

A thermistor is a temperature-sensitive resistor made of a semiconducting material. Thermistors are available with very large, either positive or negative, temperature coefficients of resistance. In most cases their stability and reproducibility are not adequate for accurate temperature measurement, but thermistors are often used in control systems.

7.4.1   Calibration of Thermistors

Many commercial thermistors are factory-calibrated. The standard calibration curve which is furnished with such a thermistor has a relatively large tolerance. If, for some application, an individual thermistor is to be calibrated, the techniques that are discussed in 7.3.1 can be used, with the difference that the reproducibility and stability of thermistors are much inferior to those of RTDs, and in consequence their calibration can be done with much simpler apparatus.

7.5   Digital Temperature Scanners

Digital temperature scanners are units capable of reading inputs including thermocouples, resistance temperature detectors, and thermistors. Temperature scanners can handle multiple numbers of input channels (16, 32, etc.) and a variety of thermocouple types. The scanners have built in isothermal blocks, analog multiplexers, and microprocessors. Connection to the main data acquisition system is via an Ethernet cable. Some of the advantages of temperature scanners include: a) ability to locate scanner in close proximity to the test engine, b) reduction in uncertainty errors due to thermocouple lead length and the number of junctions, c) cost savings due to reduced cabling and d) ability to configure an individual scanner to measure multiple thermocouple types.

8.   ROTOR SPEED MEASUREMENT

8.1   General

Almost all rotor speed signals are variable-frequency in nature. Older engines typically are equipped with tachometer generators which are coupled to the rotors by means of gears that are chosen to produce a tachometer output of approximately 70 Hz at takeoff power. Newer engines have magnetic pickups which give one pulse for the passage of each tooth on a gear, each blade of a fan, etc. In any case the measured frequency must be multiplied by a suitable constant in order to obtain a direct measure of the rotor speed, either in rpm or in percent of nominal.

8.2   Frequency-to-Voltage Converters

Frequency measurements can be made by converting the unknown frequency to an equivalent d-c voltage, using a frequency-to-voltage converter, and then measuring that d-c voltage with a voltmeter. A suitable attenuator network between the converter and the voltmeter permits the voltmeter to be calibrated for reading directly in rpm or in percent of nominal speed.

Older frequency-to-voltage converters contained a phase-locked loop with a limited rate of response to changes in the input frequency, and therefore were not suitable for dynamic studies. Also they typically had fairly large thermal coefficients, such that they had to be mounted in temperature-stabilized housings in order to achieve adequate accuracy for test cell applications.

Current frequency-to-voltage converters are greatly improved in both rate of response and in thermal characteristics. Using the reciprocal counting technique of section 8.4, along with a digital-to-analog (D/A) converter, the converters provide a high response rate analog output voltage.

8.3 Variable Time-Base Counters

Accurate frequency measurements are most easily made with electronic counters. A good quality counter will contribute a negligible error to the measurement. Most modern instruments use electronic counting techniques, which depend for accuracy on an internal oscillator that produces a very stable reference frequency. Most such oscillators are controlled by quartz crystals, so that ordinary mechanical shocks or electrical faults will not change their operating frequencies by more than a few tens of parts per million. More severe damage usually will produce a complete failure.

A variable time-base counter may be used to display rotor speed directly. The length of the time base is chosen to provide the conversion from frequency to rotor speed. For example, if a rotor with a full-speed rating of 3600 rpm delivers 30 output pulses per revolution, its output signal will have a frequency of 1800 Hz at full speed.

Measuring that signal with a counter which has a time base set at exactly 2.0 s, the counter will read 3600 at each sample, which is the actual speed of the rotor in rpm. If its time base is set at 1/1.8 of a second, 555.56 ms, and if its decimal point is moved one digit to the left, it will give a reading of 100.0 at each sample, which is the percent of nominal rotor speed.

Older engines with tachometer generators that deliver about 70 Hz output at rated speed would require excessively long counting periods to reach readings of thousands of rpm. In those cases frequency multipliers have been used successfully. Note, however, that a frequency multiplier, like the older frequency-to-voltage converters, contains a phase-locked loop with a limited rate of response to changes in the input frequency, and therefore may not be suitable for dynamic studies.

8.4 Reciprocal Counters

Another technique uses two separate electronic counters; it is called reciprocal counting. A measurement period starts on, say, the positive-going zero crossing of the rotor speed signal, and stops after some integral number of pulses or cycles of the rotor speed signal. That number is recorded by the first counter. The second counter starts and stops at the same times as the first counter, but counts timing pulses from an accurate clock (oscillator). At the end of the measurement period, the counters give the ratio of the frequency to be measured, the rotor speed signal, to the clock frequency.

With proper choices of the number of pulses of the rotor speed signal to be measured and of clock frequency, it is possible to attain a rotor speed measurement accuracy of 0.02% or better.

8.5 Digital Frequency Counters

There are many frequency counters designed to interface with a digital computer. The counters are typically mounted on circuit boards and come in single channel or multiple channel options. Depending on the manufacturer they can be stand alone or housed in a chassis. The host computer converts the counter frequency reading into a rpm value. Typically counter measurements such as frequency, period, time interval, and totalizing are available.

8.6 Calibrating Rotor Speed Instruments

A suitable variable-frequency and variable-amplitude source can be used for verifying the operation of rotor-speed measuring instruments.

9. GAS PRESSURE MEASUREMENT

9.1 General

In order to understand the performance of a gas turbine engine, it is necessary to measure pressures at many points within the engine. The critical pressures range from 12 psia (0.8 bar, or 83 kPa) to about 1000 psia (69 bars, or 6.9 MPa). Most engine test cells use electrical pressure transducers, digital indicators, and cell computers to obtain the required pressures.

Common practice is to use gauge pressure transducers, rather than absolute pressure transducers, and where necessary to convert the gauge pressure readings to absolute values by adding barometric pressure. The advantage of gauge pressure transducers is that their calibration (zero and span adjustment) is easier and faster than calibration of absolute pressure transducers, which must be pumped down to a good vacuum when their zero values are to be set. Multipoint calibration of individual transducers can be done to produce better accuracy.

Some of the required engine parameters to be measured are total, rather than static, pressures. In those cases it is important that the gas flow should strike the orifice of the total pressure probe as nearly straight on as possible.

9.2   Pressure Scanners

Because of the large number of pneumatic pressures which must be measured in engine testing, some test cell designers have chosen to use pressure scanning systems, rather than discrete transducers, for use with computer-based instrumentation systems.

The earliest pressure scanners used mechanical selector valves to connect multiple pressure channels sequentially to a single pressure transducer. The necessary channel-to-channel settling time delay and the limited life of the mechanical selector valves reduced the usefulness of these scanners.

Some pressure scanning systems dedicate an inexpensive pressure transducer to each channel and scan their readings electronically, avoiding the problems of the mechanical scanning systems. The individual transducers have excellent reproducibility but relatively poor linearity; the system achieves good linearity by storing a multipoint calibration for each working transducer and applying it in real time to each reading. These systems combine large numbers of inexpensive pressure transducers with a few master pressure transducers of secondary-standard quality, selector valves, an internal source of multiple calibration gas pressures, and a microprocessor. It scans all of the working pressure transducers, linearizes their outputs and converts them to engineering units, and transmits the data to the test cell host computer over a standard communication channel.

More recent pressure scanning systems are digitally temperature compensated. This eliminates the requirement for in cell multipoint calibration of the individual transducers thereby reducing the amount of associated equipment and cabling. The main drawback is that the scanners need to be removed periodically and calibrated against known standards.

9.3   Leaks

Leaks occurring anywhere in a pressure-measurement system will lead to incorrect pressure readings. Typically the pressure transducers will be located in the control room or some other temperature-controlled environment, and the pressure signal lines from there to the engine will be relatively long. A leak near the transducer end will have a much larger influence on the reading than a leak near the engine end.

It is good practice to check for leaks by blanking off each pressure signal line at the engine end, pressurizing it, shutting it off from the pressure source, and then observing the leak-down rate. The valves and fittings that are needed for this exercise are commonly installed near to the pressure transducers. Noticeable leaks should be located and repaired. This technique cannot test the actual connection to the engine, so special care must be taken to ensure that those fittings are made up properly.

9.4   Dynamic Pressure Measurements

A typical small-volume pressure transducer connected to a pressure probe by 30 m (100 ft) of 6 mm (1/4 in) pressure signal line will have a response time constant in the order of 1 s; that is, in responding to a step change of pressure, it will reach about 63% of its final reading in 1 s. Fortunately, ordinary post-overhaul engine testing does not require fast sampling of pressures.

For special purposes, such as studies of pressure transients at the time of a compressor stall, it may be necessary to measure fast transients. In these cases pressure transducers will be mounted on the engine under test, with very short pressure signal lines running from the pressure taps on the engine to the transducers. The transducers must be able to withstand the high engine vibrations and hot temperatures, or they may be shock mounted and cooled in some way. Continuous analog recorders, or fast sampling analog-to-digital converters, must be used to collect the transient data. Typical high speed recording equipment can capture data at a rate of 200K Hz.

9.5   Obstructions in Pressure Signal Lines

Some test cells with pressure signal pipes or hoses 3 mm (1/8 in) or less in diameter have had problems with dust, dirt, oil, or moisture due to condensation producing intermittent blockages, causing erratic behavior. The usual correction is to blow out any obstructions in the lines by means of air pressure.

With very small signal lines contaminated by liquid water, surface tension may cause the water film to form again across the signal line, even after an air pressure purge. Such a film can produce serious errors in low-pressure measurements. Lines suspected of containing water can be purged with alcohol or other hygroscopic liquids.

Signal lines 6 mm (1/4 in) or more in diameter seldom have such problems, and should be preferred wherever it is possible.

9.6   Calibrating Gas Pressure Measurements

Although liquid manometers do not require an actual calibration, they should be given a full-scale check occasionally to assure that the liquid has not been contaminated, changing its density. Other pressure measurement instruments, such as Bourdon-tube gauges, pressure transducers, etc., should have multipoint calibrations at regular intervals.

Such a calibration requires connecting the instrument being calibrated to a source of variable gas pressure, usually dry air or nitrogen, in parallel with another pressure-measuring instrument of known accuracy. Hysteresis in the instrument being calibrated can be detected by taking a set of measurements with increasing pressure and comparing them with another set taken with decreasing pressure.

10. LIQUID PRESSURE MEASUREMENT

10.1   General

The techniques used for liquid pressure measurements are very similar to those discussed in Section 9 for gas pressure measurements.

The pressure signal lines are normally filled with some of the working liquid: fuel, lubricating oil, etc. In most cases it is necessary to purge any entrapped air out of the pressure line in order to obtain an acceptable rate of response to pressure changes.

10.2   Elevation Effects

If the pressure measuring instrument or transducer is not mounted at the same elevation as the pressure tap on the engine, the weight of the liquid in the pressure line will produce a zero offset in the pressure reading. In many practical cases the effect of the static pressure head can be neglected, but when full accuracy is desired one should calibrate the instrument in place, applying the calibration pressure at the engine's end of the pressure line. Both during calibration and during engine runs one must ensure that the pressure line is full of the working liquid.

11. VIBRATION MEASUREMENT

11.1 General

In principle, the vibration of an engine under test can be measured by means of transducers which measure displacement, velocity, or acceleration. Engine vibration amplitude levels and frequencies can be used to monitor the health of an engine and help determine the problem with an underperforming engine. Reference document 2.1e contains a full discussion on engine vibration testing. This section contains excerpts from that document.

In practice, only velocity transducers, which are sometimes called vibration pickups, and accelerometers are used. Integration of the engine vibration signals are carried out to convert between acceleration, velocity, and displacement. These integrations are typically carried out electronically by the circuitry in the charge amplifier.

11.2 Accelerometers

An accelerometer contains a seismic mass mounted on a piezoelectric element, typically quartz or a special type of ceramic material, which produces an electrical charge in proportion to the force exerted on the element. Acceleration of the accelerometer body produces a force on the seismic mass and therefore on the piezoelectric element, generating an electrical charge, typically of the order of tens of picocoulombs per gravity of acceleration.

The amplifier should have a differential input, able to reject large amounts of common-mode noise. Typically the first amplifier is a charge amplifier, which accepts the electrical charge that was developed by the accelerometer and produces a low impedance voltage output that is accurately proportional to the input charge, and therefore to the acceleration.

11.3 Velocity Transducers

A typical velocity transducer contains a magnetized seismic mass sliding on a guide rod, and restrained axially by springs. When the body of the transducer is vibrated along the axis of the guide rod, the seismic mass tends to remain in a constant position, producing relative movement between the mass and the transducer body. That movement generates a voltage in an electrical coil which surrounds the magnetized seismic mass; the voltage is proportional to the velocity of movement, typically of the order of several volts per meter/second.

11.4 Mounting Locations and Brackets

For most measurements, the vibration transducers will be mounted on the engine case and gearbox. In order to make reproducible vibration measurements it is essential to mount the vibration transducers in precisely the locations specified by the engine manufacturer, and to use mounting brackets that are correctly designed to transmit the engine vibration signature without altering it.

If the vibration transducer is to be mounted in a location where the temperature exceeds the rating of the transducer, thermal insulation may be incorporated in the mounting bracket to protect the transducer from the engine heat, and some form of cooling must be provided for the transducer.

11.5 Vibration Filters

Most vibration is related to unbalance in one of the engine rotors, although occasional trouble is caused by bearings or engine accessories. Some means is needed to identify the part of the engine that is producing excessive vibration. This is normally done by means of filtering techniques. Broad-Band Vibration measurement and Narrow-Band Vibration measurement methods can be used depending on the type of engine and desired vibration data to be obtained. Proper use of filtering can provide detailed information on the various components of the engine.

11.6 Vibration Calibration & Concerns

Vibration instruments are subject to all the failure modes of other electronic instrumentation, and should be recalibrated regularly using an input signal source of known variable frequency and amplitude.

Because cabling, shielding, and grounding problems often disturb vibration measurements, good instrumentation designs make it easy to monitor the electrical signals coming to the console from the vibration transducers on the engine under test.

12. AIRFLOW MEASUREMENT

12.1 Test Cell Airflow Uniformity

High-bypass turbofan engines are particularly sensitive to lack of uniformity in intake airflow. Nonuniform airflow at the engine's air intake increases engine instability, and in severe cases may cause a compressor stall or surge. Turbojet and turboshaft engines are much more tolerant of nonuniformity in their intake airflow than turbofan engines.

A useful system for measuring the airflow patterns is a uniformly-spaced 5 x 5 (or larger) array of Pitot tubes of the type which measure both total and static air pressure, or other airflow measuring devices, located midway between the engine bellmouth and any splitter panels, turning vanes, or flow-smoothing screen upstream of the engine. The measurement should be made with the largest engine which is to be used in the test cell, running at takeoff power.

Since the engine under test is normally placed on the test cell centerline, the air entering the engine bellmouth comes from the central area. It is common practice to adjust any turning vanes, splitter panels, etc. in the front of the test cell to minimize the variations in air velocity in the central 3 x 3 group of probes. Older, low-bypass engines will tolerate larger variations in intake airflow velocity than the newer high-bypass engines.

Such measurements have proved to be useful for detecting changes in test cell performance, or for verifying that no significant change has taken place. The data from the airflow measurement array, when compared with data taken at the time of the most recent test cell correlation, will warn of changes in flow distribution which have been caused by such things as movement of a turning vane or displacement of a splitter panel. Refer to reference document 2.1l for a comprehensive report dealing with the modeling techniques for jet engine test cell aerodynamics.

Engine manufacturer typically require that engine test facilities periodically correlate their test cell along with the associated engine dress kit against a reference test cell and dress kit in order to establish the necessary correction factors. These correction factors can include a thrust correction factor, bellmouth flow discharge coefficients, and spool speed corrections. Correlation of the test cell allows for direct comparison of engine performance data between the engine manufacturer's test cells and the correlated test cell. Reference documents 2.1c, 2.1i, and 2.1j discuss in detail the recommended practices for test cell correlation of turbofan & turbojet engines, turboshaft & turboprop engines, and APU engines, respectively.

Some engine manufacturers now allow continuous trending analysis of a test facilities instrumentation and engine performance data as an acceptable alternative to periodic test cell correlation testing. In order for trending analysis to be successful, a reasonable amount of the same engine type must be tested within a set time period. Trending enables test cell personnel to monitor the results for unexplained data shifts and may help indentify facility or engine problems. Refer to reference document 2.1k for a detailed explanation on trending analysis.

12.2 Engine Airflow

The manufacturers of some engines require that the engine's intake airflow be measured as part of the normal post-overhaul test procedure. In such a case the manufacturer specifies an airflow measurement technique, which typically includes a bellmouth and calibrated duct that has been instrumented with a set of pressure probes and thermocouples. The manufacturer specifies the procedure for converting the measured pressures into airflow readings.

12.3 Bleed Airflow

The principal load on an APU or GPU under test is the flow of compressed air which it supplies, typically several pounds per second at a temperature on the order of 200-250 °C. The common method of measurement of this airflow is a sharp-edged orifice in the bleed air discharge pipe located upstream of the throttle valve that is used to control the bleed air discharge pressure.

This measurement requires computation of the airflow from knowledge of three variables: pressure drop across the orifice plate, bleed air pressure upstream of the orifice plate, and bleed air temperature upstream of the orifice plate. The calculation, if done manually, requires reference to a basic calibration curve and two correction curves. The manual technique is too time consuming for testing APUs which require the operator to adjust to a particular bleed airflow. In these cases a dedicated airflow computer, or a general-purpose test cell computer, is essential.