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TEST CELL INSTRUMENTATION

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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; they will 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 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. In a few cases the engine pressure ratio, EPR, is used instead of thrust, since in testing an engine with a given air-intake bellmouth and exhaust tailpipe the relationship between thrust and EPR is linear and reproducible.

Those 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 turbojet 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.

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:

a. "Measurement Uncertainty Methods and Applications", Dieck, Ronald H.; Instrument Society of America, 1992. ISBN 11-55617-126-9.

b. "A Short Course in Temperature Measurement", Moffat, Robert J.; 36th International Instrumentation Symposium, Instrument Society of America, 1990.

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

d. "Turbine Flowmeters Predictable Performance", Fischer & Porter Co., Warminster, PA, Technical Information Bulletin 10C-8, April 1969.

e. "Turbofan and Turbojet Gas Turbine Engine Test Cell Correlation", SAE Aerospace Recommended Practice ARP741A, 1993-09-01.

f. "Test Cell Thrust Measurement", SAE Aerospace Information Report AIR4951, in preparation.

g. "ASTM Standard Viscosity-Temperature Chart for Liquid Petroleum Products", American National Standard ANSI Z11.39.

h. “Turbine Flowmeter Fuel Flow Calculations”, SAE Aerospace Recommended Practice ARP4990, in preparation.

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 its 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 document 2.1a.

2.2 (Continued):

ALIASING: A phenomenon of sampled signals. Nyquist's theorem states that a signal which is sampled N times per second can be reconstructed completely from the samples if it does not contain significant components at frequencies equal to or greater than N/2 Hz. A higher-frequency component at M Hz, where M > N/2, will appear in the samples as a spurious frequency of M - N/2. For example, a 6 Hz sine wave sampled 10 times per second will appear to be a 1 Hz sine wave.

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, but which is not used in the combustion process. 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 mass flowrate of combustion air.

COMPRESSOR STALL: A condition in which one or more blades in the turbocompressor 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.

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.

2.2 (Continued):

K-FACTOR: In a turbine 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.

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

TURBOFAN ENGINE: A turbojet engine which draws in more air than the combustion process will use, 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 of 5.0 or more.

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.

2.2 (Continued):

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.

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.

Digital instruments can have both higher resolution and better accuracy than comparable analog instruments. They also avoid several common sources of errors: 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.

3.1 (Continued):

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.

A special pitfall of digital data is that they may be displayed with excessive precision, lending significance to meaningless digits. Suppose a pressure transducer with a total range of 10 000 psi is known to be accurate to 1% of full scale. Then for most purposes its reading should be rounded to the nearest 50 psi, or at least to the nearest 20 psi. Displaying a reading like 8736 psi leads the operator to think that the last digit is meaningful. Rounding the display to 8740, or even 8750, will avoid troubling the operator with minor noise and hysteresis in the transducer, and also will mask small fluctuations in the pressure being measured.

3.2 Static Measurements:

In usual practice, a 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 observe each parameter for a period of time, perhaps a few tens of seconds, and to calculate an average. 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 Dynamic Measurements:

Under some conditions, however, the fluctuations themselves are of interest and must be measured. It is known that nonuniformity of air flow at the engine's air intake makes the engine less stable; a very bad air flow can even cause the engine to stall or surge. Then 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. For example, one possible technique for measuring rotor speed is to connect the variable-frequency signal from the tachometer to a frequency-to-voltage converter (see 8.2) and to read the converter's output with a digital DC voltmeter. A suitable attenuator network is used so that the voltmeter may be calibrated to read directly in rpm or in percent of nominal speed.

Many frequency-to-voltage converters contain a phase-locked loop, which usually is stabilized by a single-pole RC filter. The digital voltmeter has a sampling rate of a few samples per second, which affects its response characteristics. It usually will also have a low-pass input filter, to discriminate against noise.

3.3 (Continued):

Each of these three elements acts to slow the response of the system to changes in the rotor speed. A typical system of this kind will take a second or two to reach the 90% point in responding to a step change in input frequency. Comparing its readings with those of a reciprocal counter (see 8.4) which in many cases can respond 100% in 0.1 s, the frequency-to-voltage converter will report smaller rotor speed fluctuations, making the engine appear more stable than it really is.

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:

Thrust measurement is discussed in greater depth in AIR4951, reference document 2.1f, from which most of the material following is extracted.

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.

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, or a pair of load cells in compression. (This discussion neglects the special requirements of multi-axis thrust stands, which are outside its scope.)

4.2 Errors in Thrust Measurement:

With well-designed thrust stands, the load cells are the principal source of errors in thrust measurement. Their imperfections include curvature of the transfer characteristic, hysteresis, drift, creep, temperature coefficients, and nonreproducibility. Serious errors may be produced by side loading of the load cell; that is, by nonaxial forces, and by thermal gradients in the load cells, which may be 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.

4.2 (Continued):

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.

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 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. Unfortunately, mounting a dummy engine and connecting a push or pull to it at the level of the engine centerline is relatively time-consuming; such a thrust calibration typically takes an hour or two, and therefore is not performed frequently.

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, of course, to make a centerline thrust calibration cross-check on any new thrust stand, and occasional comparison tests to make sure that the characteristics of the thrust stand have not changed.

The calibration load cell and its associated thrust indicator serve as a secondary standard. As such, they should be sent out periodically to a standards laboratory which can calibrate them together, as a system, 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 or by dynamometers of various types, including water brakes. The useful power output of the engine under test is the product of the output shaft speed and its torque.

Although a few engines have built-in torque measurement systems, best practice is to equip the test facility with accurate torque instrumentation which can readily be sent out for calibration traceable to a national laboratory standard.

5.2 Shaft Torque Measurement:

The most accurate commercial shaft torque measuring instruments use strain gauges, mounted on the shaft and rotating with it, to measure the torque which the shaft is transmitting. 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.

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 torque measurement systems 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 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:

Fuel flow is always specified in gravimetric, mass flow, terms. Although some mass flowmeters are available, fuel flow is usually measured by means of a volumetric, volume flow, device plus knowledge of the density or specific gravity of the fuel. Some positive displacement meters, similar to the fuel-truck-mounted meters that measure the quantity of fuel delivered to an airplane, are in use, but most installations depend on turbine-type flowmeters.

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:

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 time base must be properly related to the K-factor, given in counts per unit volume, of the flowmeter, for volumetric output, or to both the meter's K-factor and the current fuel density, for gravimetric output.

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 so-called 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. Document 2.1h contains a detailed discussion of flowmeter errors and calibration techniques.

6.2 (Continued):

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.

The manufacturers' ratings of turbine flowmeter accuracy assume measurement periods that correspond to many turns of the turbine. 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.

6.3 Viscosity Effects:

Changes in fuel viscosity will affect a turbine-type flowmeter's turn-down rating. In general, the higher the fuel viscosity, the larger the flowmeter's departure from linearity in the low-flow region. 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 by doubling the low-end flow rate below which the flowmeter's K factor can no longer be regarded as constant.

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 picked off from the universal viscosity curve and used to calculate the volumetric flow rate.

If no viscometer is available, one can have each batch of fuel analyzed by the supplier. A minimum of two viscosities, at widely-spaced temperatures, is required, say at 40 °C and at -18 °C. Viscosities at other working temperatures can then be estimated either from a plot on Chart D341 of reference document 2.1g, or by the calculation given in the Annual Book of ASTM Standards, Section 5, Designation: D341-93. It should be noted that plots on Chart D341 always yield straight lines, hence two correct points suffice.

If the actual viscosity of the fuel batch is not obtainable, one can obtain average viscosities for the type of fuel in use and follow the procedure above to estimate the working viscosity at a given working temperature.

Although the universal viscosity curve is only an approximation to the actual behavior of a turbine meter, as explained in reference document 2.1d, 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 (see 6.3). 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.

6.5 Flowmeter Calibration:

Recalibration of a flowmeter is seldom possible in the field, except by comparison with another flowmeter connected in series with it. Other than catastrophic failures, turbine flowmeters typically degrade gradually as their bearings wear. Some users maintain a master flowmeter, which has been calibrated at a standards laboratory and is used only infrequently, for comparison with their working flowmeters.

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 Figure 3 of reference document 2.1c, 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 Mass Flowmeters:

Mass flowmeters typically are based on the Coriolis effect; the fuel flows through vibrating tubes. In recent years a number of commercial mass flowmeters have been introduced which have accuracy ratings that are acceptable for gas turbine engine testing. Such meters require no density corrections and are not affected by fuel viscosity changes. At present there has not been much experience with these instruments in engine testing, but it seems probable that their use will increase rapidly.

6.8 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.

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 under arctic conditions, to that of burning fuel, which may be as high as 2000 °C.

7.2 Resistance Temperature Detectors:

Engine inlet air temperature should be measured accurately, because of the sensitivity of engine performance to inlet air density. Although older 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 good-quality platinum RTD will have a working error less than ±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 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 an 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°, so that the bath temperature can readily be observed to 0.05°. 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.

7.5 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 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.

7.6 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 will follow standard tables, such as those from NIST, within stated limits of error.

Thermocouple manufacturers state that their products will meet the standard NIST tables of temperature versus output EMF within the following tolerances, 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. Then the thermocouple error limits the system accuracy.

TABLE 1

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

7.7 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 almost never 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, except that the temperature of the junction between the thermocouple leads and the extension wires replaces the "reading" or hot junction temperature in the calculation. Extension wires of premium quality have approximately half of those errors.

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.

7.8 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.

7.9 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.

Older instruments, particularly those used in aircraft, may have a low enough input resistance to load the circuit significantly, reducing the thermal voltage delivered to the indicator. Most such instruments are calibrated for service with a known thermocouple circuit resistance, which is chosen to be higher than any that is anticipated. Such an instrument is installed with enough added series resistance to obtain the desired total circuit resistance. No other instrument can be connected in parallel with such an indicator without calibration problems.

7.10 Calibration of Thermocouple Systems:

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

There are many possible causes for misbehavior of a thermocouple. An ideal thermocouple may give incorrect readings because of heat conducted through its leads or its mounting, radiation effects, and other environmental problems. Reference 2.1b discusses such matters at length. 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.

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.

Until recently all 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.

The newest frequency-to-voltage converters are greatly improved, both in rate of response and in thermal characteristics, by using the reciprocal counting technique of 8.4, together with a digital-to-analog (D/A) converter to produce an 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.

8.3 (Continued):

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:

A more recent 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 simple to attain a rotor speed measurement accuracy of 0.02% or better.

8.5 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 13 psia (0.9 bar, or 90 kPa) to about 500 psia (34 bars, or 3.4 MPa). In typical test cells, liquid-column manometers and Bourdon-tube gauges are rapidly being replaced by electrical pressure transducers and digital indicators.

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 by zero and span adjustment is much faster than calibration of absolute pressure transducers, which must be pumped down to a good vacuum when their zero values are to be set.

Some of the 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.

9.1 (Continued):

Many of the pressures in a running engine have fast fluctuations which are several times as large as the allowable error in the pressure reading. Usual practice is to damp the signal, that is, to reduce its fluctuations, by means of a restriction in the pressure signal line.

9.2 Pressure Scanners:

Because of the large number of pneumatic pressures which must be measured in jet 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.

More recent 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.

Such a system combines 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.

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. The system can be approximated as being equivalent to a single-pole low-pass filter between the probe and the transducer, cutting off, 3 dB down, at 0.16 Hz. 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 those 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.

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, and condensation moisture 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. In practice, only velocity transducers, which are sometimes called vibration pickups, and accelerometers are used. Most U.S.A. engine manufacturers specify vibration limits in units of displacement, while most European engine manufacturers specify them in units of velocity or acceleration. Even with a complex vibration signal containing many frequency components, an acceleration signal can be converted into an equivalent velocity signal by means of a single integration, or into an equivalent displacement signal by means of two integrations. These integrations reduce the sensitivity of the system to high-frequency vibrations; conversely, they increase its sensitivity to low-frequency vibrations.

It is not possible to make such conversions by simple calculator multiplications, except for pure sine-wave signals of known frequency. Measurements made with narrowband filters (see 11.6.2) are an exception, as the output of a narrowband filter approximates a sine wave. Complex vibration signals require actual integrations.

Although in theory it would be possible to convert a velocity signal to an equivalent acceleration signal by means of a differentiation, this is not done in practice because differentiation enhances high-frequency noise.

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.

This charge is a relatively weak, high-impedance signal, which therefore is subject to electrical noise interference. Special low-noise cable should be used between an accelerometer and the first amplifier in the system, to prevent mechanical vibration of the cable from generating spurious electrical signals caused by triboelectrical effects. Relative motion between mating connectors in this circuit can produce spurious signals similarly.

Great care is needed in grounding accelerometer systems. Ground loops may inject excessive hum and noise into the circuit. 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.

Some manufacturers now offer accelerometers which contain one or more stages of amplification within the accelerometer housing. This avoids the triboelectrical effects which were discussed above, permitting use of ordinary electrical cabling. In many cases, however, the amplifier will not tolerate as wide a temperature range as the accelerometer will, limiting the application of the instrument.

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.

This relatively strong and low-impedance signal is less vulnerable to electrical noise and triboelectric effects than the weak high-impedance signal from an accelerometer. It is still desirable to avoid ground loops and to use an amplifier with a differential input stage to reject common-mode noise.

11.4 Mounting Locations and Brackets:

A few aircraft engines have accelerometers permanently mounted within the engine, usually on a major bearing. For most measurements, however, the vibration transducers will be mounted on the engine case. Aircraft engine designers go to great lengths to keep the engine as light as possible. In consequence, the engine case is relatively flexible, and its vibration patterns will vary substantially from place to place.

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 vibrations without modifying them. It is best to use the types of vibration transducers which are recommended by the engine manufacturer, and to purchase mounting brackets from the engine manufacturer.

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 Thrust Stand Effects:

The thrust of an engine has small rapid fluctuations which are discussed in 4.2. The fluctuations shake the engine and the thrust stand. The resulting vibrations look like low-frequency random noise, and are often spoken of as "thrust stand noise". Vibration instruments for use with turbojet engines usually have high-pass filters cutting off at around 10 or 20 Hz to suppress that noise, which is acceptable since the noise is not related to engine performance.

Some of the vibration characteristics of the engine under test are influenced by the way in which the engine is mounted. Engines which are tested with nonresilient supports, like the RB211, may be more affected by details of thrust stand and adapter design than engines which have supports with controlled spring constants, like the JT9D and the CF6.

11.6 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.

11.6.1 Broad-Band Vibration Measurement: In testing older engines, band-pass filters are commonly used in the vibration instruments to separate the vibrations caused by the different rotors, since they turn at quite different speeds.

In comparing vibration measurements made in different test cells with different vibration instruments, a frequent source of difficulty is the filter specification. For example, a bandpass filter for a particular engine might be specified to pass vibrations from 40 to 115 Hz, with a 3-pole - asymptotic to 18 dB/octave - attenuation curve above and below the passband.

11.6.1 (Continued):

Unfortunately, some manufacturers specify the pass frequencies at the 95% gain point (5% attenuation, or 0.45 dB down), while others specify them at the 71% gain point (29% attenuation, or 3 dB down). Also, when dealing with multipole filters, the designer may choose to use Butterworth, Tschebyscheff, elliptical, or other filter designs, with a bewildering variety of parameters. The effect of such variations depends on the amount of vibration energy in the affected frequency regions. It may range from negligible to 50% of the reading or more.

Another difficulty is the detection specification. In reading peak-to-peak values, older vibration instruments, and some current ones, use averaging detectors with the output meter calibrated to read 3.14 times the average voltage. This gives the correct peak-to-peak voltage only if the signal is a sine wave. Some newer instruments use rms detectors, with the output meter calibrated to read 2.83 times the rms voltage. This is more satisfactory than an averaging detector, but still is not precise. It is also possible to measure the true peak-to-peak value directly with a relatively elaborate detector. With a typical complex vibration waveform, the three types of detectors will give readings that vary substantially.

If the filter specifications and detector specifications of the vibration instruments in the post-overhaul test cell are equivalent to the specifications of the instruments in the manufacturer's baseline test cell, the broad-band vibration measurements should agree reasonably well. If the specifications are quite different, the two instruments, both working correctly, may differ by as much as 2:1 in measuring a given vibration signal. Without detailed knowledge of the vibration frequency spectrum and the instrument specifications, it is not possible to predict how the two readings will compare.

11.6.2 Narrowband Vibration Measurement: The manufacturers of many of the newer engines specify that vibration measurements are to be made with a narrowband filter. Such measurements are less affected by details of the filter and detector design than are broadband measurements, so that better agreement with the manufacturer's data can be expected.

Many of the narrowband filters can be automatically tuned to the rotation frequency of one of the engine rotors, following it as the rotor speed changes. Such a filter is called a tracking filter. Tracking filters are very convenient, making it simple to detect rotor unbalances, but they cannot be used in studying any significant vibration peaks that do not correspond to a rotor speed. For such studies the operator must tune the filter manually over the frequency range of interest.

11.6.2 (Continued):

The operator must use care in working with narrowband filters, which typically have bandwidths of the order of 5 to 10 Hz. Some such filter designs have constant bandwidth, others have constant Q, which means that the ratio of center frequency to bandwidth is constant. With any such filters it is important not to tune across a vibration peak too rapidly; the output of a filter with a 5 Hz bandwidth takes about 1 s of constant input to reach full response. Tuning across the peak too rapidly, or changing the engine speed too quickly, when sweeping from idle to takeoff, will reduce the apparent size of the peak. Also, some of the engine's mechanical resonances may be fairly high-Q, in electrical engineers' parlance, and therefore will take time to build up to maximum amplitude as the rotor speeds change.

11.7 Trim Balancing the Engine:

Although the engine shop will have balanced the individual rotors of the engine as well as they can, it is commonly observed that the completely-assembled engine will have excessive vibration and should be further balanced in the test cell. This is called trim balancing. In high-bypass engines, the fan has by far the largest potential for causing vibration, and it is common practice to trim balance the fan in the test cell. Turbojet engines and many afterburning engines do not have fans. Some operators will perform trim balancing of such engines in the test cell, but it is difficult and slow because of limited access to the affected rotors.

Obviously, balancing the fan cannot compensate for unbalances of the high-speed rotor, or even for unbalances of parts of the low-speed rotor that are well aft of the fan. If balancing the fan does not bring the total engine vibration within acceptance limits, other unbalances must be corrected either in the test cell or in the shop.

It is possible to balance a rotor by the so-called three-shot method, in which one adds test weights at arbitrary locations and observes their effects on the vibration amplitude. This procedure is relatively slow and requires many starts and stops of the engine. With turbofan engines, where normally only the fan is to be trim balanced, a substantial amount of test cell time and fuel consumption can be saved by adding instrumentation which measures the phase of the engine vibration relative to a reference angle on the fan. With such instrumentation, it is often possible to achieve acceptable fan balance on the first attempt at adding a balancing weight.

The fan reference angle may be established by marking a blade in some way, often with a strip of reflecting tape, and observing its passage optically. The resulting signal is referred to as a 1/rev (one pulse per revolution) signal. Many of the newer engines provide a reference angle by modifying a single pulse in the group of pulses from the fan rotor speed pickup. That pulse may be made either higher or lower than the other pulses, so that a pulse height discriminator in the trim balance system can select the marker pulse and use it as a reference.

There are many sources of phase-shifts in any trim balancing system; the amplifiers, the filters, the mechanical properties of the engine case, even the engine supporting system can alter the apparent phase of the unbalance peak relative to the fan reference angle. In each test cell a phase angle offset constant must be found experimentally for each engine model and for each rotor speed which is to be used for balancing.