



AEROSPACE INFORMATION REPORT

AIR5026™**REV. B**

Issued 1996-11
Revised 2014-10
Reaffirmed 2020-10

Superseding AIR5026A

Test Cell Instrumentation

RATIONALE

AIR5026 is being revised ahead of the five-year reaffirmation in order to include recommendations on steady-state data acquisition (3.2). This revision provides guidelines on data acquisition minimum sample rate, sample averaging time and the calculation of additional parameters based on steady-state data.

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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

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 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.

- (a) ARP741 Turbofan and Turbojet Gas Turbine Engine Test Cell Correlation
- (b) ARP4755 Turboshift/Turboprop Gas Turbine Engine Test Cell Correlation
- (c) AIR4827 Modeling Techniques for Jet Engine Test Cell Aerodynamics
- (d) AIR4869 Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cells
- (e) AIR4951 Test Cell Thrust Measurement
- (f) AIR4989 Design Considerations for Enclosed Turboshift Engine Test Cells
- (g) ARP4990 Turbine Flowmeter Fuel Flow Calculations
- (h) AIR5295 Design Considerations for Enclosed Turboprop Engine Test Cells
- (i) ARP5435 APU Gas Turbine Engine Test Cell Correlation
- (j) ARP5758 Trend Analysis for Maintaining Correlation of Gas Turbine Engine Test Cells
- (k) ARP6068 Gas Turbine Engine Test Facility Vibration Measurement

2.1.2 Other Publications

- a. "Measurement Uncertainty: Methods and Applications", 4th Edition, Dieck, Ronald H.; ISA – The International Society of Automation, 2007, ISBN-13: 978-55617-915-0.
- b. "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 $\pm 0.5\%$ of full scale value, or $\pm 2\%$ 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 2.1.2 (a).

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.

UNCERTAINTY: 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.

For test cells with a computerized data acquisition system, best practice recommendations for steady state measurements are:

- All measurements should be sampled at the same rate and averaged over the same time interval.
- A sample rate sufficient to encompass typical stabilized engine parameter variation should be used. It is recommended that data be sampled at a minimum of 10 Hz for a minimum of 10 seconds (e.g., 10 Hz for 10 seconds = 100 samples averaged), unless other (higher or lower) frequency sampling combined with appropriate averaging duration provide repeatable results.
- Calculated parameters should be based on final averaged data (rather than calculating value for each sample and then averaging the individually calculated values over the time interval).

3.3 Transient Measurements

Measurement of an engine's 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.

Non-uniformity 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 2.1.1 (e), 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.