Module - 5

ENGINE TESTING & TYPES OF ENGINE TESTING

Syllabus:

Engine Testing:

Proof of Concepts: Design Evaluation tests. Structural Integrity. Environmental Ingestion Capability. Preliminary Flight Rating Test, Qualification Test, Acceptance Test. Reliability figure of merit. Durability and Life Assessment Tests, Reliability Tests. Engine testing with simulated inlet distortions and, surge test. Estimating engine-operating limits. Methods of displacing equilibrium lines.

Types of engine testing:

Normally Aspirated Testing, Open Air Test Bed ,Ram Air Testing, Altitude Testing, Altitude test facility, Flying Test Bed, Ground Testing of Engine Installed in Aircraft, Flight testing. Jet thrust measurements in flight. Measurements and Instrumentation. Data Acquisition system, Measurement of Shaft speed, Torque, Thrust, Pressure, Temperature, Vibration, Stress, Temperature of turbine blading etc. Engine performance trends: Mass and CUSUM plots. Accuracy and Uncertainty in Measurements. Uncertainty analysis. Performance Reduction Methodology.

5.1 Tests done for performance and quality validation

Engineering evaluation test:

- These tests are conducted for the purpose of acquiring data (for safety, installation, maintainability, quality, etc.) to establish that an engine configuration is capable of completing the PERT and QT.

Preliminary flight rating test (PERT):

- The preliminary flight rating test is the sum of test, demonstration and analysis activity to demonstrate suitability of engine model for the flight testing.

Qualification test (QT):

- These are tests, demonstration and analysis activity accomplished on engines and components for qualification to demonstrate the suitability of engine for production use.

Acceptance test (AT):

- The acceptance tests are subset of QT's conducted on engines submitted for acceptance under contact to demonstrate correct assembly and performance to the extent specified in the engine configuration.

5.2 Design evaluation tests

Customer air bleed:

- This is a bleed air test to verify air bleed flows required for aircraft system use.

Engine heat rejection and oil cooling:

- Engine designers are being pressured to design more efficient engines to decrease emissions and fuel consumption.
- To achieve these design goals, the trend is pointing toward engine downsizing and having higher compression ratios in order to increase power output.
- Increasing the power output, in turn, creates higher demand on thermal heat management.
- The high thermal loads will generate thermal stresses, which could lead to shorter engine life, or failure.

Oil flow interruption test:

- Engine shall be operated at the intermediate power setting of 30 seconds with only air supplied to the inlet of the oil pump.

Engine power failure:

- Electrical power interruptions and switch over to alternative source of power should meet MIL-E-5007 D.

Engine vibration survey:

- The spectrogram should cover frequency range 5 – 10000Hz.

Starting torque and speed:

- The starting and the testing of gas turbine engines will be performed each time the engine is overhauled, taken out of preservation, or each time the engine encounters a problem which affects its working parameters. There are some references about starting and testing procedures.

Maintenance demonstration:

- Maintenance demonstration for 300 hrs.

Material corrosion test:

- Corrosion testing is fundamental to understanding how materials perform under simulated service conditions and can help to ensure that they will reach their projected design life.

5.3 Structural integrity

Structural life:

- The structural life shall be based upon the distribution of power settings for the requirements and utilization rates and for percentage of temperature exceeds versus ambient temperature.

High cycle and low cycle fatigue life:

- For low cycle fatigue testing (LCF), the test is run in strain control with the load as a dependent variable. LCF is characterized by high amplitude, low-frequency plastic strains. Low cycle fatigue can be particularly useful in industries that rely on materials in temperature-varying and cyclic conditions including aerospace, architecture, automotive, oil and gas, and power generation industries.
- high cycle fatigue (HCF) services that can help in determining the fatigue strength of a particular material through a variety of tests including but not limited to:
    - Axial Fatigue (ASTM E466)
    - 3-Point Bend Fatigue
    - 4-Point Bend Fatigue
    - Cantilever Fatigue
    - Rotating Beam Fatigue (RR Moore style)

  High cycle fatigue testing is typically conducted on specimens in load/stress control to develop Stress-Life (S-N) Curves. An S-N Curve is generated by testing samples at a constant load/stress and recording the number of cycles to failure. The data is then compiled and a best trend fit is applied. This establishes a relationship between a particular load/stress level and the fatigue life of the material.

Engine pressure vessel/case design:

- Should withstand 2 times its wax operating pressure without rupture.

Containment and rotor structural integrity:

- Containment – The engine shall completely contain a fan, compressor, or turbine blade failure at the blade airfoil section in the fillet at maximum allowable transient rotor speeds.
- Rotor integrity – The rotor shall stand the following abnormal conditions:
  - Rotor speed of 115% of maximum allowable measured gas temperature for 5 minutes.
  - Measured gas temperature at least 42 degree centigrade in excess of maximum allowable steady state rotor speed for 5 minutes.

Disk burst speeds:

- Shall not be less than 122% of the maximum allowable steady state speed.

Vibration:

- Vibrations generated by engine outside the specified frequency range shall not be detrimental to engine operation. The limits shall be based on the engine being installed in a mounting system which will be following dynamic characteristics.
- The natural frequencies of the damping system with the engine installed shall be no higher than 80% of the rotor speed(s) in all modes of vibration which can be exited to the residual rotor unbalances.

5.4 Environmental ingestion capability

Bird ingestion:

- When enquired by user services, the engine shall be capable of ingesting the number and different sizes of birds at the bird velocity and engine speed as described by MIL-E-5007D.
- The number of birds to be ingested shall be based on the area at the fan/compressor base.

Foreign object damage (FOD):

- The engine shall operate for two inspection periods or the number of hours specified in the engine specification after ingestion of defined FOD.

Ice ingestion:

- The engine shall be capable of ingesting hail, and any ice which accretes on engine inlet parts without flameout.

Sand ingestion:

- The engine shall be capable of operating at maximum continuous thrust with specified concentration of sand and dust for a total of 10 hours with not greater than 5% loss in thrust, 5% increase in SFC.

Atmospheric liquid water ingestion:

- The engine shall operate satisfactorily with up to 5% of total airflow weight in form of water.

5.5 Preliminary flight rating test (PFRT)

Endurance test:

- Number of cycles, throttle position, incremental rotation speed run, thrust transient run, reverse thrust run, maximum continuous thrust form part of this test. After test, recalibration of engine is done.
- The procedure during the engine calibration shall be such as to establish the entire performance characteristics of the complete engine. Before and after the test, the engine should be calibrated.

Power Lever Torque:

- Torque is an important mechanical quantity in many applications.
- Measuring torque precisely, in particular on rotating parts, places high demands on test bench manufacturers and users.
- There are two different approaches to determining torque: the direct and the indirect method.

Engine Component Tests:

- Previous component approval
- Explosion proof test in accordance with MIL-STD-810
- Fire test for lines carrying flammable fluids

Altitude test:

- Minimum engine performance, transient, distortion, wind milling, relight and restart are demonstrated through altitude test.
- The engine should be capable of at least 5 hrs. of continuous Wind milling operation throughout its entire operating envelope without damage to the engine, and without affecting capability of air restart.
- The engine shall be started, and operated at intermediate power lever operation for at least 3 minutes, at each of the six test points as shown in flight operating envelope.

Engine pressure rest:

- All gas pressure loaded components and engine are subjected to 2 times the maximum compressor discharge pressure without rapture.

Rotor Structural Integrity test:

- Rotor speed 115% of max allowable at max allowable gas temperature for 5 minutes.
- Disc burst speed 122% of maximum allowable.

Engine Static Load Test:

- Static load test is done for externally applied forces, 1.5 times, to demonstrate the capability of the engine and its support. It is done in a static rig. In this test, maximum thrust loads, ‘g’ loads, gyroscopic moments, torque and engine reaction loads will be applied separately and then in combination. Stress and deflection data will be obtained at critical locations.
- Gyroscopic test is done in steps from 0.5 rad/see to and including 3.5 rad/sec. in step increments of 0.5 rad/sec.

Vibration test:

- Max permissible limits at each accelerometer location on engine compressor and turbine cases, accessory gear box case, and if applicable, intermediate structure shall be specified.
- The overall velocity limit specified for each accelerometer shall be applicable up to a frequency of 10,000 Hz.

Electromagnetic Interference und Susceptibility Tests:

- It should be done prior to endurance test on all electrical/electronic components as per MIL-STD-461. The test shall be conducted in accordance with the methods, procedures and techniques of MIL-STD-462.
- Acceleration spectrograms shall be provided for critical components covering frequency range of 5 Hz to 10 kHz and present data in peak g's.

Critical speeds:

- A 20% margin shall exit between the maximum operating speed and critical speed. Adequate damping should be provided if an engine passes through a critical speed below idle.

Vibration and stress analysis:

- The critical speeds, excitation frequency and stress values for the vibration stress values for the vibration stress distributions and same patterns shall be determined and correlated with strength and life cycles.

5.6 Qualification test (QT)

In addition to PERT, the following tests are conducted towards qualification testing for release to service:

Endurance test:

- The endurance test shall consists of two segments of 150 hours each conducted on each of two engines and conducted as per endurance test procedure.

Environmental ingestion:

Life assessment test:

- To establish TTL/MTBO/Calendar life/Servicing periodicity, shelve life and storage conditions.

High cycle fatigue and low cycle fatigue criteria:

Reliability:

- To establish MTBF

Repair procedures and wear limits:

Accelerated aging on non-metallic parts:

- Subject to dry air ambient temperature for not less than 71^{0} C, for a minimum of 168 hours.

Humidity:

- Components are subjected to humidity condition test cycle of time relative humidity and temperature.

Fungus:

- Compared to non-nutrient materials.

Corrosion susceptibility:

- Salt laden air or NaCl used for test.

Armament gas ingestion:

- Engine shall be operated without stall, surge, flameout or damage as a result of armament gas ingestion. Tests are specified for various power settings and altitudes and for aluminized gas.

Nuclear hardening:

- Radiation hardening is the act of making electronic components and systems resistant to damage or malfunctions caused by ionizing radiation (particle radiation and high-energy electromagnetic radiation), such as those encountered in outer space and high-altitude flight, around nuclear reactors and particle accelerators, or during nuclear accidents or nuclear warfare.

- Radiation-hardened products are typically tested to one or more resultant effects tests, including total ionizing dose (TID), enhanced low dose rate effects (ELDRS), neutron and proton displacement damage, and single event effects (SEE, SET, SEL and SEB).

Rotor cross section test:

Infrared radiation test:

- Infrared and thermal testing is one of many Nondestructive testing techniques designated by the American Society for Nondestructive Testing (ASNT). Infrared Thermography is the science of measuring and mapping surface temperatures.
- Infrared thermography, a nondestructive, remote sensing technique, has proved to be an effective, convenient, and economical method of testing concrete. It can detect internal voids, delamination, and cracks in concrete structures such as bridge decks, highway pavements, garage floors, parking lot pavements, and building walls. As a testing technique

5.7 Acceptance test

Acceptance tests are conducted on each engine submitted for delivery. These tests are subset of QTs, prepared by engine contractor and are submitted for approval by user service as an acceptance test procedure (APT) document.

Acceptance tests of gas turbines with emission control and/or power augmentation devices that are based on fluid injection and/or inlet air treatment are also covered by this International Standard and it is necessary that they be considered in the test procedure, provided that such systems are included in the contractual scope of the supply subject to testing.

This International Standard does not apply to emission testing, noise testing, vibration testing, performance of specific components of the gas turbine, performance of power augmentation devices and auxiliary systems, such as air inlet cooling devices, fuel gas compressors, etc., conduct test work aiming at development and research, adequacy of essential protective devices, performance of the governing system and protective systems, and operating characteristics (starting characteristics, reliability testing, etc.).

5.8 Reliability

- Reliability is the ability to perform a required function under stated conditions for a stated period of time.
- Reliability qualification involves three phases: apportionment, prediction and analysis. Maintainability qualification follows a similar approach.
- Failure mode, effect and criticality analysis (FMECA) and fault tree analysis are helpful qualitative tools for design assurance.
- Reliability prediction is a continuous process starting with paper prediction based on design analysis, plus historical failure rate information. The evaluation ends with reliability measurement based on data from customer use of product.

5.8.1 Reliability figure of merit

Mean time between failures (MTBF):

- Mean time between successive failures of a repairable product (total engine hours accumulated in measurement period divided by the number of failures in the measurement periods).

Failure rate:

- Number of failure per unit time.

Mean time to failure (MTTF):

- Mean time to failure of a non-repairable product.

Mean life:

- Mean value of life (life may be related to major overhaul, wear out time, etc.).

Mean time to first failure (MTFF):

- Mean time to first failure of a repairable product.

Mean time between maintenance (MTBM):

- Mean time between specified types of maintenance action.

Longevity:

- Wear out time.

Availability:

- Operating time expressed as a percentage of operating and mean time.

Percentage of life:

- Life during which X% of the population would have failed.

Repairs/X:

- Number of repairs per X operating hours.

5.8.2 Reliability definitions

Engine failure:

- Inability to obtain or sustain thrust at any if the required levels as a result of an engine component failure.
- An inflight thrust loss 10% or greater of the minimum power normally available for specific power setting.
- A condition charged to engine, which causes or generates a decision to shut engine or retard throttle to reduce engine thrust greater than 10% of the proper desired value. Engine flameouts chargeable to engine are considered engine failure.
- Low oil level after flight indicating warning.
- High vibration levels.
- If fault is corrected by component replacement.

Excluded failure:

- Maintenance/repair lapse
- FOD
- Failure resulting when engine was operated beyond specification
- Fuel/oil contamination

Mean time between failures:

- MTBF is defined as the total engine hours accumulated in the measurement period divided by the number of failures in the measurement periods.

5.9 Durability and life assessment tests

To achieve successful and sustainable commercialization, building products must meet three important criteria, namely minimum cost, sufficient performance, and demonstrated durability.

Durability assessment directly addresses all three segments of this triad. First, it permits analysis of life cycle costs by providing estimates of service lifetime, O&M costs, and realistic warranties. Understanding how performance parameters are affected by environmental stresses (for example by failure analysis) allows improved products to be devised. Finally, mitigation of known causes of failure directly results in increased product longevity. Thus, accurate assessment of durability is of paramount importance to assuring the success of solar thermal and building products.

- **PENALTY** is the level at which an assessment is made of the economic effects of a component failure. Based on this assumption, it is possible to set a reliability level that must be maintained for a given number of years.
- **FAILURE** is the level at which performance requirements are determined. If the requirements are not fulfilled, the particular component or part of component is regarded as having failed. Performance requirements can be formulated on the basis of optical properties, mechanical strength, aesthetic values or other criteria related to the performance of the component and its materials.
- **DAMAGE** describes the stage of failure analysis at which various types of damage, each capable of resulting in failure, can be identified.
- **CHANGE** is related to the change in the material composition or structure that can give rise to the damage of the type previously identified.
- **EFFECTIVE STRESS** is the level at which various factors in the microclimate, capable of being significant for the durability of the component and its materials, can be identified. An important point here is that it is possible to make quantitative characterization.
- **LOADS**, finally, is the level that describes the macro-environmental conditions (climatic, chemical, mechanical), and which is therefore a starting point for description of the microclimate or effective stress as above.

5.10 Reliability tests

Reliability testing can generally be looked at as any interruptions in usage or performance during the lifetime span of a product, part, material, or system.

Good products seek to minimize the unexpected interruptions in performance throughout the duration of the typical of customer experience. So good testing looks to maximize, catch, or expose these unexpected interruptions in performance during product evaluation, and the conditions in which these interruptions occur.

Depending on whether we are conducting Performance Testing, Durability Testing, Reliability Testing, or any combination thereof, the Environmental Factors or Conditions with Our Multiple Test Chambers and Testing Equipment to Determine the Operating Limits of Your Products, Parts, and Materials:

- Aging
- Lifetime Span
- Operational Limits
- Component Degradation
- Failure Points
- Material Testing
- Tensile Testing
- Burst Testing
- Environmental Testing
- Soak Rooms / Chamber
- Load Testing

The variety of Tests and Test Chambers to Test Product and Part Limits:

- Pressure Cycling / Pressure Cycle Testing
- Vacuum Cycling
- Thermal Cycling, Temperature Testing
- Thermal Shock Testing
- Mechanical Shock and Vibration Testing
- Soak Rooms
- Salt Spray / Corrosion Testing
- Slosh Testing

- Permeation, Evaporative Emission Testing, Helium Leak Testing
- Carbon Canister Testing – Load and Purge Cycles and Loads
- Fuel Delivery R&D
- Pump – Durability Testing, Performance.
- Filter – Durability, Performance
- Level Sender – Durability, Slosh Testing
- Module – Durability Testing, Performance Testing

5.11 Engine testing with simulation of sir inlet distortion

Reduction of compressor stall margin, instability of combustion, lower combustion efficiency, local overheating engine, etc., frequently occur as a result of inlet flow distortions. Following are methods for inlet distortion modeling.

- Distortion screens installed in the cylindrical
- Ducted nozzle simulation technique
- Free jet testing

Inlets operating at off design conditions have flow non uniformities occurring frequently. The attitude variations cause increases distortions. Tests actually simulate the inlet duct conditions: shock wave formations, boundary layer development, etc.

Free jet testing approximately doubles the air handling requirement of the test facility in order to assure interference free inlet conditions at the engine inlet. Frequently the necessary air handling capacity for free jet testing is not available in a test facility. In such cases, the air can deducted directly (direct connect) and without appreciable spillage to the engine inlet so that approximately half the capacity required for a free jet facility is needed.

5.11.1 Inlet distortion screen method

A support grid over which screens of various densities and arrangements can be placed is located upstream of the engine in the ducting. By selection of the density and the number of the overlapping screens, the local pressure distribution turbulence profile in the inlet can be controlled.

The operating limits of a turbojet engine are represented for non-distorted, two sector type distorted, and one sector type distorted inlet flow. At high Reynolds numbers, influence of the disturbances is relatively small. The small margin in the high speed range id practically unaffected; the stall margin in the low speed range shows only a slight change.

At low Reynolds number, corresponding to high altitude flight conditions, the effect of inlet flow distortion on the stall margin is extremely critical, particularly in the high speed range.

5.11.2 Ducted-nozzle distortion methods

It is frequently not sufficient merely to determine the sensitivity of an engine to given standard types of airflow distortion patterns; it is often necessary to closely simulate the actual airflow distortion pattern occurring at the engine inlet at various flight conditions. In many cases the ducted nozzle method can be utilized to provide such improved simulation of inlet flow distortion instead of the more costly simulation method provided by either free jet or propulsion wind tunnel testing where the airflow and plant capacity requirements are much greater.

A major portion of the inlet duct is duplicated in the ducted nozzle technique. Simulation of the disturbances which originate ahead of the inlet duct is then produced by adjustable vanes, thus a wide range of distortion patterns is possible.

For a given freestream Mach number and angle of attack, the distortion pattern depends primarily on pressure level in combustion chamber that is, on the intensity of the combustion or on the fuel air ratio. Hence a strong inter-relationship exists between the combustion intensity and the pressure recovery and air flow distortion in the inlet duct.

The simulated distortion gets strongly influenced by the movement of shock downstream of the duct throat in supersonic flow. This shock move upstream or downstream depending upon the pressure level in combustion chamber. A systematic study is therefore required without adjustable vanes to determine to what extent the correct distortion profiles can be simulated by merely adjusting the Mach number in the narrowest section to the proper value determined previously in the wind tunnel tests. The effective area of the ducted nozzle throat can be varied by insertion of wedges or by blowing in or sucking off air.

The different response rate of the boundary layer build-up in the inlet ducting throttle transient movements may introduce deviations which require specific investigation before the suitability of the ducted nozzle technique for each individual test could be assured.

It is relatively easy to discharge the exhaust gases passing through the engine at a higher pressure than the ambient altitude pressure. This can be done by applying the choked-nozzle technique in which the engine exhaust gases are not expanded to the ambient pressure but only to a pressure slightly below that required to choke the exhaust nozzle.

This method permits the study of all internal conditions up to and including the throat of the exhaust nozzle, but it does not provide simulation at the correct conditions in the downstream portion of the exhaust nozzle. Even in this case the exhaust gases can be expanded to low pressure levels corresponding to ambient pressure then recompressed by the use of supersonic diffuser or ejectors before they enter the exhaust duct.

Alternatively the kinetic energy of the bypass air is used to increase its pressure level before it is discharged in to the exhauster, based on the principle of the supersonic second-throat diffuser. This method utilizes a shroud which is fitted tightly to the free-jet supersonic nozzle to avoid mixing of the bypass air with the air in the surrounding chamber until after the bypass air has been raised to a higher level. The pressure recovery potential for the bypass now in free-jet assemblies is, however much poorer than the pressure recover potential of conventional supersonic wind tunnels. This situation results from the fact that the boundary layer along the internal walls of the supersonic nozzle is a considerably larger portion of the mass flow through the supersonic nozzle, because the high energy core of the supersonic nozzle flow is added through the engine. As a result, it is obviously exceedingly difficult to recover the energy of the supersonic bypass flow. The boundary layer thickness, therefore, needs to be reduced. Such suction will be produced in actual configurations by separate auxiliary ejectors.

The most important effect of air distortion is the reduction of the stall margin. The stall margin is defined as the difference in compressor pressure ratio between the steady-state equilibrium operating line and the stall-limited pressure ratio.

Distortion affects the acceleration time. The reduction in margin between the steady-state operating line and the stall limit reduces the excess torque available for engine acceleration. At higher altitudes, the increase in acceleration time may become larger. These effects are predictable from component tests with properly simulated inlet distribution.

5.11.3 Free - Jet Test Methods

For both the distortion screen and the ducted nozzle methods, the test facility must supply air only to the extent directly required by engine; a very small additional amount of external airflow is needed for breathing or cooling purposes. These two techniques also require wind tunnel tests preceding the actual hot engine tests for determination of the correct distortion pattern.

If such artificial means of producing the desired inlet distortion pattern are not satisfactory and if test facilities of sufficient capacity are available, the so called free-jet test method which represents a significant improvement in the natural production of inlet flow distortion may be employed.

One major requirement for free-jet testing is that disturbances originating at the supersonic jet boundary must not propagate into the inlet flow to the engine. Since at large angles of attack such a condition is sometimes difficult to meet, critical inlet flow patterns are observed by means of the shadow graph, method to determine whether or not an externally-originated shock or disturbance is interfering with the inlet flow.

The limitations imposed on the free jet testing method have resulted in a limitations of the maximum permissible test article size. In general, 50% or more of the supersonic nozzle flow must be bypassed around the engine. This value is somewhat larger at high angles of attack.

5.11.4 Methods of initiating surge – Displacement of equilibrium working line

For an HP compressor the most usual method is fuel spiking. Here the working line is raised by momentarily injecting excess fuel, between 10% and 400% extra over around 200ms.

For LP compressors or fans the most usual method is to build a development engine with a reduced capacity LP turbine or bypass nozzle respectively, to raise the working line. Bleed extraction is used to enables operation at higher power, the engine is then slowly decelerated until it surges. The process is repeated with various levels of bleed to map out the surge line.

Other less common technique includes in bleeding air downstream of the subject compressor.

5.12 Factors for design of engine test beds

- Engine inlet flow is uniform. Any distortion will affect compressor performance and will give an erroneous mass flow measurement. At worst, vortices may be shed from the floor or walls causing high cycle fatigue failure of compressor blades.
- There is no reinjection of hot exhaust gas. Should this occur the resulting distorted inlet temperature profile will again affect compressor performance. It will also prevent accurate measurement of inlet temperature, which is essential for referral of measured engine performance.
- For thrust engines, that the static pressure field around the engine is as close as practical to that of free stream conditions. As described below the thrust reading must be corrected for this effect: the smaller the effect the less scope for error in the correction.
- The static pressure distribution at the propelling nozzle exit plane allows accurate determination of a mean value. Otherwise the thrust measurement will be in error, and the engine performance may be affected.

5.13 Test bed calibration

Test bed calibration enables data from an indoor test bed to be adjusted to reflect infinite atmosphere conditions. In addition, engines of a given mark may be tested on more than one test bed, each with a different configuration and hence different calibration factors.

5.13.1 Test bed definitions

Test bed approval is a formal process, involving regulation by the appropriate airworthiness authority for aircraft engines, and high customer involvement for other engine types. The following basic definitions apply, though other similar terms are also used:

- **‘Gold’** standard test bed:
    - This is the datum for cross calibration of all other beds for that engine type. Such calibration may be performed directly or via calibration of an intermediate ‘silver standard test bed.
- **‘Silver’** test bed:
    - This has been directly cross calibrated against the gold standard test bed. It may be used for cross calibration of other beds for that engine type.

- **‘Bronze’** test bed
    - This has been calibrated against a silver test bed. It may be used for performance testing, but not for calibrating other test beds.
- **Functional** test bed
    - This test bed has not been calibrated for performance purposes, and provides results that are indicative only.
    - Such a test bed may be useful for endurance testing or demonstrating the functionality of a production engine, but not its performance.

A cross calibration exercise normally involves comparing results obtained running the same engine on two test beds, without any transportation of test bed slave equipment. The benefits of cross calibration are dubious for engine configurations where transportation between test beds would require significant rebuild.

For thrust engines, the gold standard bed for the first engine of a type is declared by calibration versus an outdoor test bed, i.e. infinite atmosphere. For shaft power engines direct calibration of the mass flow measurement is required.

5.14 Steps in test bed cross calibration

The object of cross calibrating a test bed is to reproduce the performance measurements obtained on the gold standard test bed, after referral to standard conditions, such as ISA sea level static. The steps involved are:

- All test bed instrumentation is calibrated.
- An uncertainty analysis is performed to determine the likely errors in all measurements and derived parameters accumulating from all sources.
- Calibration curves (i.e. sequences of throttle settings) are run on both test beds, consisting of around a dozen stabilized points from idle to maximum rating.
- Ideally a ‘1–2–1’ sequence is used with the gold or silver bed as ‘2’; here any faults may be detected based on history. For example, the curve of inlet depression versus mass flow should be well known, and any deviation during the calibration run should be detectable. For the bed to be calibrated there may be no such history, hence having two runs proves repeatability. Other test sequences may be employed where high confidence levels make the cross calibration more of a confirmatory exercise.

- The physical configuration of the bed being calibrated is adjusted during the last test if necessary, with respect to how it affects air flow and hence thrust measurement. This includes inlet and exhaust details, engine position, and auxiliary equipment in the cell.
- Finally calibration factors are derived and are tabulated, versus speed say, for use in all future testing. These are the differences in thrust, air flow and station temperatures and pressures.

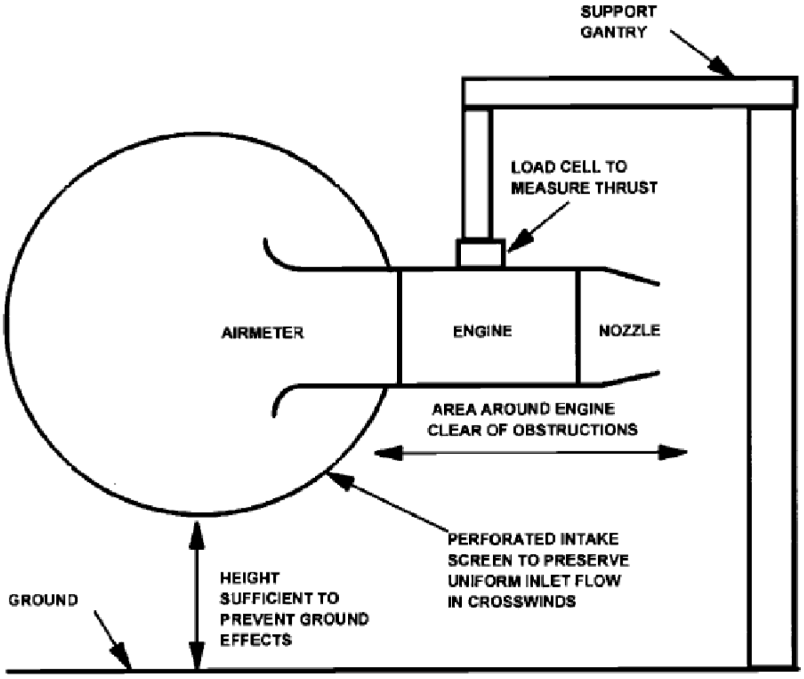
5.15 Normally aspirated testing (Types of test beds)

- Both engine manufacturers and airlines share the requirement to test the engine to determining performance, verify repairs and ensure proper function of each engine component.
- In general the various types of test activities can be divided in two categories:
  - research and development and
  - production.
- Within the research and development category four different types of test can be identified namely,
  - the design test,
  - the proofing test,
  - the capability test and
  - the trouble shooting test.
- All of them are aimed at supporting the engine manufacturer in the development and the certification of the engine.
- The production tests include the acceptance tests post-overhaul. Although this need not be done necessarily by the engine manufacturers it must meet the design authority specification.
- Engine test facilities are designed to assess engine operation and performance under well controlled conditions.
- They are divided into two types,
  - the Sea-level Test Facility (SLTF) and
  - the Altitude Test Facility (ATF).
- The most common is the sea-level test facility where the engine operates atmospheric conditions.

- The Altitude Test Facility is provided with extensive compressor, exhauster, heater and dryer equipment in order to independently control the temperature and the pressure at the engine inlet and exhaust. In such a way the engine operates under a wide range of conditions simulating different altitude and Mach number.

5.16 Outdoor sea level thrust (Open air) test bed

- This is consists basically of an open air stand supporting an engine and providing thrust measurements.
- The effects of cross wind on entry conditions are neglected by a large mesh screen fitted around the engine inlet.
- The immediate test bed area is free of obstructions to the air flow, to ensure the validity of the thrust and air flow readings.
- This is the most definitive thrust test bed, as for indoor test beds the thrust and air flow measurements are corrupted by the flow field generated by the sidewalls.
- Outdoor test beds are sited in remote areas, to minimize the environmental disturbance of the noise produced.
- Because of the resultant logistic difficulties and the impact of adverse weather conditions, indoor testing is preferred in most countries, with measurements calibrated versus outdoor facilities.

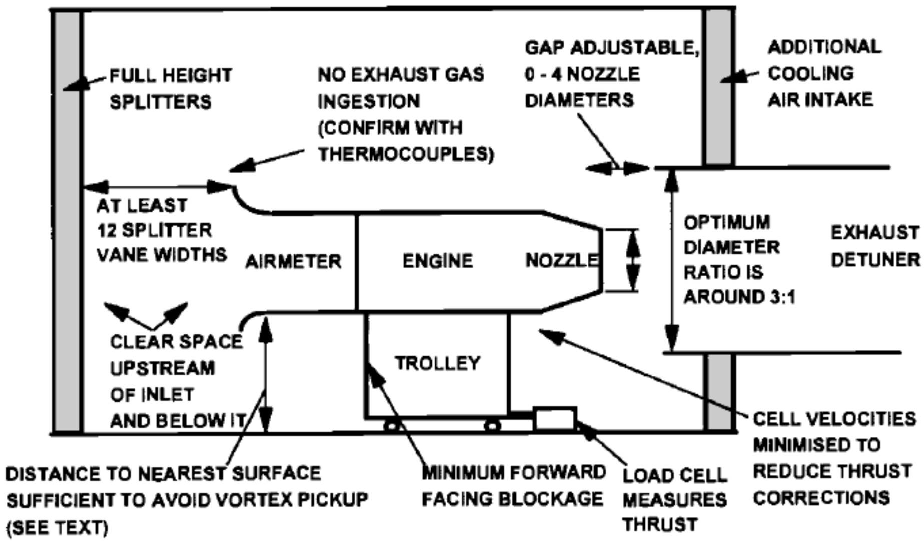


Notes:
To minimise noise disturbance outdoor test beds are normally sited in remote areas.
Climatic conditions also influence choice of location.

Fig. 11.1 Outdoor sea level thrust test bed.

5.17 Indoor sea level (Ram air / Enclosed) thrust test bed

- The test bay (or test main chamber) is the section where the engine is located in its thrust measurement stand during the test.
- From the control room the engine is fully controlled during the test. Often, this is also the room where all the data acquisition systems and data reduction processors are located.
- The equipment room is dedicated to the storage of the compressed air for the cell and the engine, fuel for the engine and all the components for providing the engine with the needed power electricity.



Note:
Sea level gas generator test bed is similar but without thrust measurement.

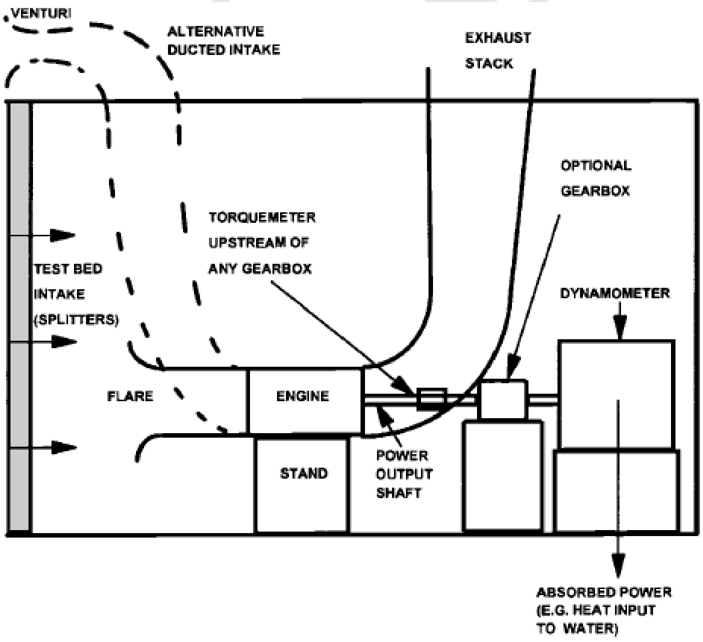
Fig. 11.2 Indoor sea level thrust test bed.

- The air flow path to the engine is crucial, as flow disturbance must be minimized. The engine nozzle efflux enters a detuner, which exhausts hot gases and provides sound attenuation.
- For a given engine the measured thrust may be up to 10% less than the value that would be recorded on an outdoor test bed. This is due to unrepresentative static pressure forces acting on the engine and cradle, caused by the velocity of air within the cell passing around the engine.
- This air is entrained into the detuner by the ejector effect of the engine jet; it prevents hot gas re-ingestion and also cools the detuner.
- Furthermore, if the engine final nozzle is unchoked the test bed configuration can cause a rematch due to the local static pressure distribution at the nozzle exit.

- An indoor test bed gives useful all-weather availability, but unless the test bed is purely functional it should be calibrated against an outdoor test bed, to determine the effects of the static pressure field and rematch.

5.18 Indoor sea level shaft power bed

- This is used for turboprop or turboshaft engines, with output power measured directly.
- The main differences from an indoor thrust bed are as follows.
  - Air may be ducted directly to the engine from ambient rather than it flowing though the test cell, with flow measured outside the test bed at entry to the ducting. The test bed configuration does not affect measured air flow and hence measured performance; the building is only there to provide protection from adverse weather conditions.
  - Alternatively air may enter the test bed through splitters and then into the engine as per a thrust bed; here test bed configuration does affect the measured air flow and the rules provided should be adhered to.
  - The exhaust flow has a low velocity and is ducted directly to atmosphere with no detuner required. Entrainment effects therefore need not be considered.

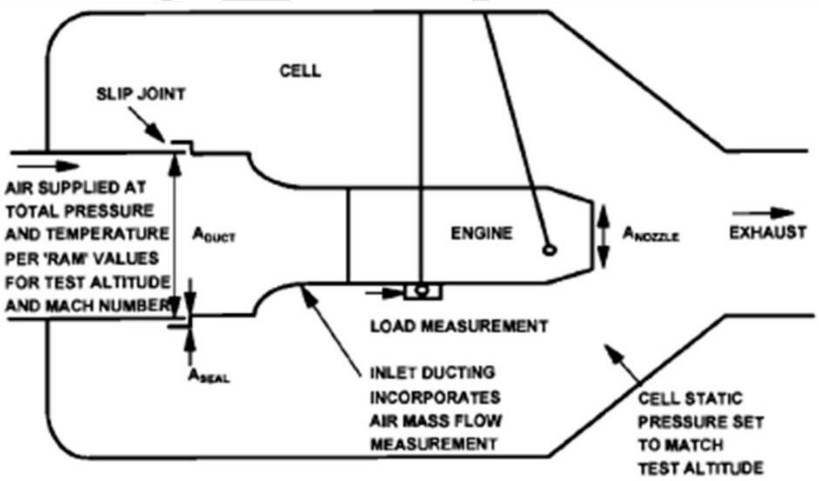


Notes:
If flare used for mass flow measurement, positioning guidelines are per Fig. 11.2.
Shaft power test bed has almost no entrained air flow.
If a gearbox is used to match power turbine speed to dynamometer then torque/power measurement must exclude gearbox losses.

Fig. 11.3 Indoor sea level shaft power test bed.

- On shaft power test beds some device must absorb the engine output power, providing suitable characteristics of load versus speed. There are several possibilities:
  - For a turboprop, an aircraft propeller may be fitted on the test stand.
  - An alternator may be used to generate electrical power, to be either dissipated in electrical resistance banks or passed to a grid system. The latter is appealing environmentally, but usually impractical during an engine development programme. Set up costs are high, rotational speed is tied to grid frequency, and intermittent operation may be unacceptable to a grid operator.
  - A dynamometer absorbs power over a range of power and speed combinations, and often also measures torque. In the hydraulic type a vaned rotor and stator arrangement pumps water through the vanes. The power absorbed heats the water, which must either be cooled or a fresh supply provided. Valves control the water level within the dynamometer, which changes the power absorbed at any given speed and allows for various power/speed laws. Torque measurement utilises a load arm and weighing system on the external casing, which is freely mounted on bearings. The input torque is transmitted via the water and any bearing friction.

5.19 Altitude test facility (ATF)



Notes:

$$\text{GROSS THRUST} = \text{LOAD} + A_{SEAL} * (PS_{SEAL} - PS_{CELL}) + A_{DUCT} * (PS_{DUCT} - PS_{CELL}) + W_{DUCT} * V_{DUCT}$$

$$\text{NET THRUST} = \text{GROSS THRUST} - W_{DUCT} * V_O$$

W_{DUCT}, LOAD, PT_{DUCT}, T_{DUCT}, PS_{CELL} and PS_{SEAL} are measured directly.
V_{DUCT} and PS_{DUCT} are calculated from the measurements using Q curves (see Chapter 3).
V_O is flight velocity, calculated from static temperature and flight Mach number.

Fig. 11.4 Altitude test facility (ATF).

- Thrust or shaft power test beds may be housed within an altitude test facility (ATF), which reproduces the inlet conditions resulting from altitude and flight Mach number.
- Unlike a sea level test bed the plant must provide a continuous airflow even without the engine operating, to maintain reduced pressure and temperature.
- To simulate both ambient conditions and flight Mach number engine inlet total pressure and temperature must be controlled to the ram (free stream total) values for the altitude and Mach number.
- Also, the static pressure at the nozzle exit plane must be set to that of the test altitude.
- These parameters are mostly sub ambient at altitude, hence common features of the various types of ATF are substantial pressure reduction, chilling and drying capabilities, and recompression of discharge air back to ambient.

Advantages:

- A full of ambient and flight conditions can be tested at one geographical location.
- High availability, independent of weather conditions.

5.20 Flying test bed

- A flying test bed is also often used for major aero-engine programmes.
- Typically a four engine aircraft is modified to mount a single, new development engine at one berth.

- Compared with an ATF the advantages are:
  - Better simulation of functional effects such as carcase loads and inlet distortion
  - Lower capital cost
- However as mentioned there are no direct measurements of thrust and mass flow. These must be calculated as follows.
  - Propelling nozzle thrust coefficient and capacity are obtained from rig and engine tests, ideally in an ATF.
  - Nozzle entry total pressure and temperature are measured directly, with sufficient coverage to obtain valid average data.
  - Nozzle mass flow may now be calculated, along with exit velocity,
  - Any air offtake and nacelle ejector flows are estimated from design data.
  - Fuel flow is measured directly.
  - Inlet air flow may now be calculated,
  - Net thrust is the difference between the total exit and inlet momentum, and if the nozzle is choked any pressure thrust must be added.

5.21 Ground testing of engine installed in aircraft

The engine is tested for determining the static installed thrust using the ground operating procedures.

Just as starting procedures will vary with engine type, so will controls and instrumentation vary with airplane types. Almost all gas turbine engine equipped airplanes will have the following levers, switches and instruments to control and indicate engine operation.

- Power lever
- Fuel shutoff valve
- EPR gage (turbojet or turbofan only)
- Percentage of rpm gage
- EGT or TIT gage
- Fuel flow gage
- Oil pressure and temperature gage
- Torque meter gage (turboprop or turboshaft only)
- Starter switch

- Engine master switch
- Fuel booster pump switch, pressure gage and light
- Ignition switch

In addition following may be additional control and instrumentation:

- Nozzle position indicator
- Vibration indicator
- Feathering switch (turboprop only)

5.22 Engine ratings

Turbojet and turbofan engines are rated by number of trust these are designed to produce for:

- Takeoff
- Maximum continuous
- Maximum climb
- Maximum cruise ratings

Engines installed in commercial airplanes are usually part throttle engines, that is, takeoff rated thrust is obtained at throttle settings below full throttle position. Part throttle engines are also referred to as flat rated due to the shape of the takeoff thrust curve used for such engines.

The ratings for these operating conditions are published in the Engine Model Specification for each model engine. Takeoff and maximum continuous ratings, being the only two engine ratings subject to FAA approval, are also defined in the FAA Type Certificate Data Sheet. Engines installed in commercial aircraft are usually "part-throttle" engines; that is, takeoff-rated thrust is obtained at throttle settings below full-throttle position.

"Part-throttle" engines are also referred to as being flat rated, due to the shape of the takeoff thrust curves used for such engines. What is actually meant by the term flat rating is perhaps best described by comparing takeoff thrust settings on the military "full-throttle" engines with the "part-throttle" commercial engines.

The "full-throttle" engine is adjusted under sea-level standard (SL Std.) conditions to produce full-rated thrust with the throttle in full forward position. Ambient temperature changes occurring with the throttle in full forward position will cause thrust level changes. Temperatures rising above the SL Std. 15°C will result in a proportional thrust decrease, while at temperatures below standard, thrust will increase, exceeding the rated level as shown in Fig. 19-12.

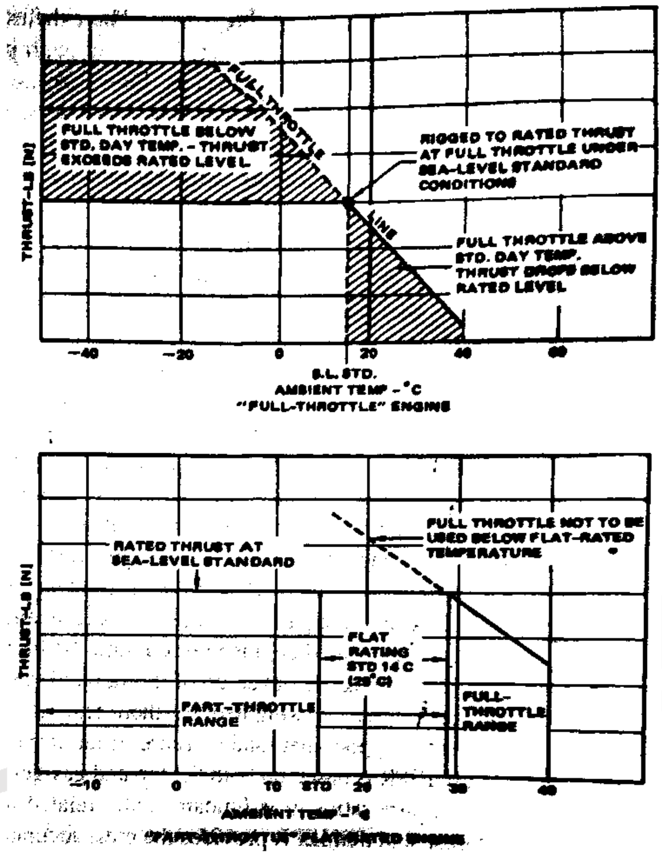


FIGURE 19-12 Thrust rating versus ambient temperature for "full-throttle" and "part-throttle" engines. (General Electric.)

For maximum reliability, better hot day performance, and economy of operation, commercial turbojet and turbofan engines are operated at the more conservative "part-throttle" thrust levels, thus in effect making them "flat-rated." A flat-rated engine is adjusted under sea-level standard conditions to produce full-rated thrust with the throttle at less than full forward position. When ambient temperature rises above the SL Std. 15e C, rated thrust can still be maintained up to a given temperature increase by advancing the throttle. The amount of throttle advance available to keep the thrust level "flat rated' is determined by engine operating temperature limits.

As an example, the takeoff thrust of the General Electric CF6-6 high-bypass turbofan engine is flat rated to sea-level standard day (15^{o}C) plus 16°C = 31°C, at which point thrust becomes EGT limited. Any further increase in ambient temperature will cause a proportional decrease in thrust.

At ambient temperatures below SL Std., the thrust is held to the same maximum value as for a hot day. In this manner a flat-rated engine can produce a constant rated thrust over a wide range of ambient temperatures without overworking the engine.

5.23 Engine flight testing

Performance tests on a test stand will not give the thrust of the engine installed in the airframe. The air intake location and the aircraft flow field interference are unique, resulting in changes to thrust values known from static conditions. Thus there is need to establish in-flight thrust values. Engine flight testing involves in the following,

- Thrust estimation
- Engine handling characteristics
  - Air starts
  - Bode or engine acceleration
  - Afterburner lights
- Performance and test maneuvers

5.24 Thrust estimation

There are a number of methods available to the flight test engineer for inflight thrust measurement on jet power aircraft. However, like power determination on a reciprocating engine powered aircraft, they all have their weaknesses.

5.24.1 Jet flow measurement

- One of the more common methods is called the jet flow measurement method. This method works reasonably well on all types of jet engines and can be used as a check on other methods.
- The gross thrust is determined by measuring the engine pressure ratio (EPR) and solving for gross thrust by use of the equations.
- The thrust coefficient is determined by measuring the thrust as a function of EPR during a ground static calibration and plotting Cr as a function of EPR as shown in Fig. 7.1.
- This ground static calibration should be conducted for each test installation and should be repeated if any engine or airframe component is changed during the test. Since during the ground static calibration it will not be possible to obtain as high a

value for EPR as will be obtained in flight, the plot of Cr vs EPR must be extrapolated to the higher values of EPR. It is this extrapolation that is the most likely source of error in the method.

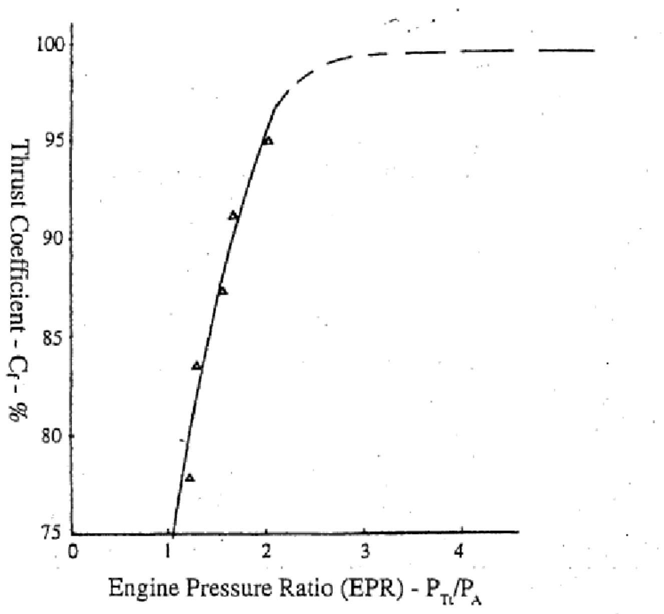


Fig. 7.1 Thrust coefficient vs EPR from static ground calibration.[1]

5.24.2 Engine Manufacturer's Data

- Another method for in-flight thrust determination is the use of the engine manufacturer's thrust curves and engine calibration data.
- This is one of the least accurate methods since it does not account for installed thrust losses, and the engine thrust calibration is normally only conducted at sea level.
- This method would be used only when schedule time or budget restraints did not allow use of a more accurate method

5.24.3 Wind Tunnel calibration

- If the facilities are available, a calibration of the engine in altitude-capable wind tunnel with the operational inlet and nozzles installed can provide accurate values of both gross thrust. This data may then be used for determining thrust in flight.
- Care must be taken to insure that the engines used in the flight test and the wind tunnel calibration have the same thrust characteristics.
- It is preferred to use the same engine for the flight tests as was calibrated in the tunnel, since there may be considerable variation in thrust from engine to engine of the same design.

- This method costs a large sum of money and is normally only available to those testing military aircraft.

5.24.4 Climb Performance Method

- The jet flow method of thrust determination can be criticized for the fact that its accuracy is dependent upon the determination of the thrust coefficient and that values must be extrapolated to EPRs that can be obtained in flight. There is also a question about the effects of altitude on thrust coefficient.
- A method developed by the French called the climb performance method removes some of the inaccuracies of the jet flow method and is actually more of an extension of that method than a method that stands alone.
- We can assume that the values of thrust coefficient obtained during the ground static calibration are accurate at low flight speeds and low altitudes.
- If we then determine the net thrust by this method in a low altitude climb at best rate-of climb speed, we can assume it is accurate.

5.25 Engine trimming

Operational engines must occasionally be adjusted to compensate, within limits, for thrust deterioration caused by compressor blade deposits of dirt or scale or other gas path deterioration. This process is called trimming.

The word comes from the old practice of adjusting the engine's temperature and thrust by cutting or trimming the exhaust nozzle to size. Although the nozzle size on some engines can be varied by the insertion or removal of metal tabs called mice, the trimming process generally involves a fuel-control adjustment to bring the engine to a specific temperature, fuel flow, thrust, and engine pressure ratio. Manufacturer instructions must be followed when performing trimming operations on any specific engine. Trimming on of newer engines is automatically accomplished through the digital engine electronic control (DEEC), of which the fuel control (FADEC) is a part.

When the rated thrust cannot be restored without exceeding other engine limitations, the engine must either be field cleaned or removed and sent to overhaul. Cleaning is accomplished by introducing a lignocellulose material into the air inlet duct while the engine is operating. The cleaning material, known as Carboblast Jet Engine Type, is made by crushing apricot pits or walnut hulls. Specific steps to follow in cleaning any particular engine are to be found in the maintenance instructions for that engine. These steps generally include blocking some lines and ports and removing any equipment in the inlet duct that might be damaged by the cleaning material. The engine is then run at different speeds for stipulated periods of time while the Carboblast compound is fed into the inlet duct. After cleaning, the installation must be returned to its original configuration and the engine must be retrimmed.

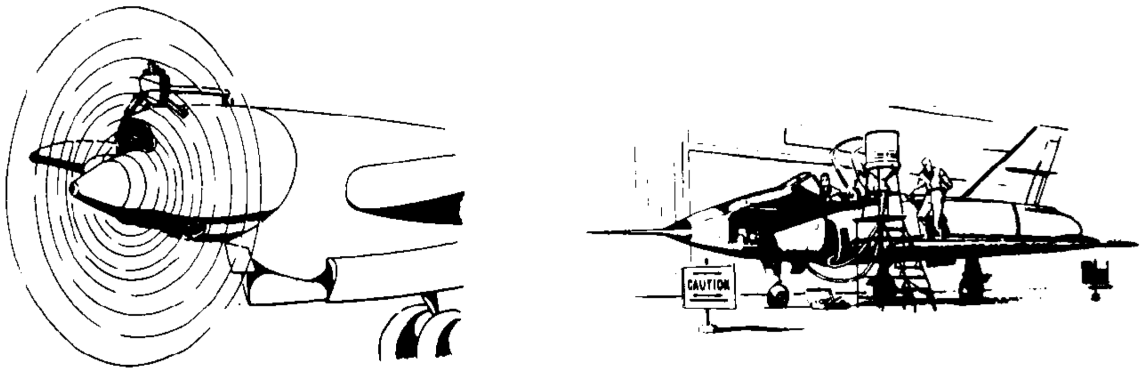


FIGURE 19-13 Cleaning turbojet and turboprop engines by grit-blasting.

On some engines, cleaning is accomplished by using a washing solution consisting of plain water or an emulsion of demineralized water, kerosene, and other cleaning liquids such as Turco 4217. This type of field cleaning is done either as a desalination wash to remove salt deposits when operating in salt-laden air or as a performance recovery wash to remove dirt and other deposits that build up over a period of time depending on the environment. After cleaning, the engine may be motored with the starter or run. The use of a water wash is not recommended after the use of a dry chemical fire extinguisher.

5.26 Engine log sheet

Most manufacturers will have an engine log sheet on which is recorded the following data in addition to the instrument readings.

- Engine model and serial number
- Serial number of component
- Grade and specific gravity of fuel
- Grade or specification of oil
- Test cell depression (pressure drop due to test cell inlet restriction)
- Total time of test cell run
- Reason for unscheduled shutdown
- Repair made to engine during test

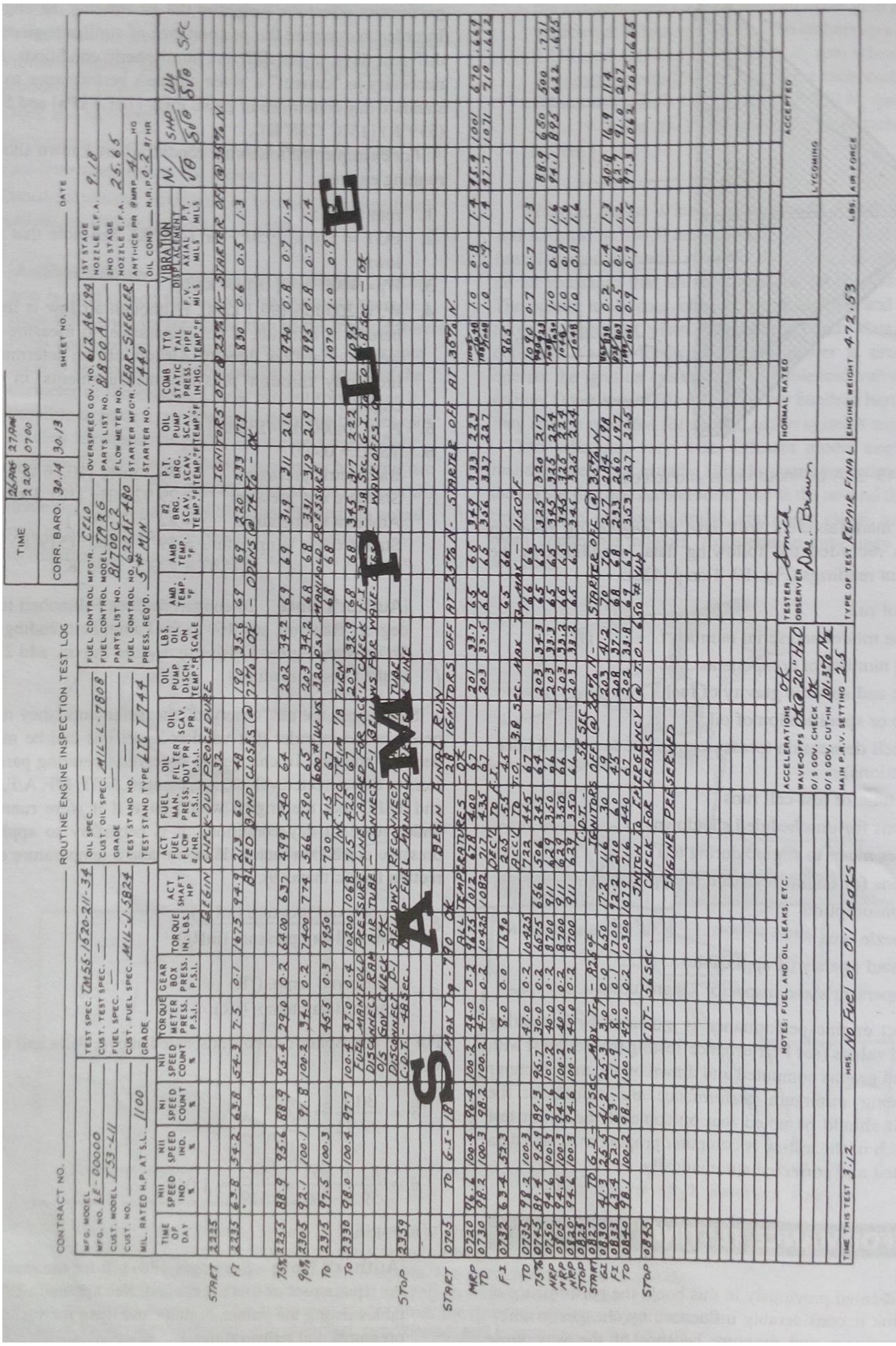


FIGURE 19-4 An AlliedSignal Lycoming T53 engine test log.

- Reason for engine rejection (if applicable)
- Oil consumption

- Jet nozzle area
- Overhaul agency (if applicable)
- Test operators and inspectors signature

Correct engine performance is indicated for standard day conditions and compared with manufacturers guaranteed performance by comparing corrected value with charts and graphs drawn by the manufacturer guaranteeing minimum performance and values for the engine.

5.27 Measurements and instrumentation

Engine tests use differing amounts and sophistication of instrumentation, depending on their purpose. Many development tests require detailed performance investigation, hence pressures and temperatures are measured at virtually every station, as well as power or thrust, shaft speeds, fuel and air flow, etc.

At the other extreme, for production pass off or endurance testing only a minimum of measurements are taken beyond those of the production control system, such as ambient conditions, power or thrust level, and fuel flow.

Engine testing is very expensive, hence to ensure good quality data is obtained the importance of the following cannot be overemphasized.

- The test bed and all instrumentation must be properly calibrated.
- Test planning should include careful specification of instrumentation requirements.
- Key measurements must be repeatedly checked during the testing, to ensure data is valid. Engine removal from the test bed must be delayed, and testing repeated, if necessary.

5.27.1 Pressures

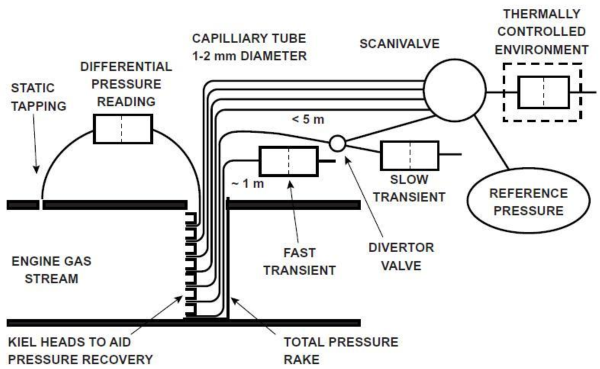


Fig: The main elements of a typical pressure measuring system

Pressures are measured for a number of reasons:

- Determination of overall engine performance requires ambient or cell pressure so that parameters can be referred back to standard conditions.
- Engine station pressures help define component performance, e.g. pressure ratios, surge margins and flow capacities.
- Mass flow measurement is based on the local difference between total and static pressure levels.

Manometers:

- For pressures below around 2 bar older test beds have used water or mercury manometers, where the height of a column of liquid in a glass tube is read visually.
- Small corrections are applied for the temperature of the liquid column.
- For a well-designed system accuracy is around 0.25%. As automatic data recording has become more prevalent manometers have virtually disappeared.

Transducers:

- Modern test beds use a transducer, where a pressure difference causes movement of a diaphragm, which is converted to an electrical signal.
- The other side of the diaphragm may be at ambient pressure or a vacuum, giving gauge and absolute readings respectively.
- The diaphragm movement is converted to a voltage, which is read by the data logging system.
- For many transducers the conversion uses an energizing voltage and a resistive strain gauge on the diaphragm. Alternatives are piezo-electric, which generate their own voltage, or inductive.
- Calibration curves relate the electrical signal to pressure levels, and are obtained by either a dead weight tester which applies a known force and hence air pressure, or comparison with other calibrated transducers.
- Transducer designs are optimized for various pressure ranges; selection should ensure operation is in the most linear part of the range, typically 10–90% of full scale.
- Transducer temperature should be controlled as this affects the strain gauge resistance; even compensating circuitry does not fully eliminate the effect. Accuracies quoted herein are for a controlled transducer temperature.

- Steady state, typical accuracies are around 0.1% of full scale for the basic transducer, however a good overall accuracy is 0.5% for engine pressures. This figure allows for calibration drift, hysteresis, engine stability and pressure profiles, transducer non-linearity, and drift in the voltage supply.
- Cell static pressure is less prone to engine effects hence an accuracy of 0.25% is obtainable.

Comments on pressure measurements at the various engine stations are presented below:

Ambient pressure – barometers:

Barometers are used to measure ambient pressure, with an accuracy of around 0.1%. They fall into two main categories:

- An aneroid barometer consists of a dial and pointer controlled by an evacuated metal cylinder with corrugated sides and a spring action. Changes in ambient pressure cause movement which is read on the dial.
- A mercury in glass or Fortin barometer uses a mercury column in a closed glass tube, evacuated at the closed, upper end.

Test cell static pressure:

- This is required for all engines where the intake is inside a test bed, and is measured in at least two places of low cell velocity.
- Usual locations are on the side walls in the plane of the nozzle exit, at the same height as engine centerline.
- The instrumentation comprises the open end of a 1–2mm diameter capillary tube surrounded by a perforated 'pepper pot', which removes the effects of incident velocity.
- The tube is then connected to either a transducer or water manometer.

Engine static pressures:

- If the axis of a tapping is perpendicular to the flow direction then it will read static pressure, as no dynamic head will be recovered.
- These give a more accurate reading than side or rearward facing toppings on immersed probes, as the presence of the probe disturbs the flow.
- Static pressure trappings may be used in place of total pressure readings if a calibration has already been obtained versus the total pressure reading.

- Such calibrations become tenuous however if there is swirl angle variation, as this changes the local Mach number.

Engine total pressures:

- To achieve full recovery of the stream dynamic head, and hence measure total pressure, the pressure tapping is mounted in a probe which points its axis towards the direction of gas flow.
- If the flow angle varies by more than $\pm 5^0$, a Kiel head should be employed.
- This uses a chamfered entry to recover effectively the stream dynamic head for incidences of up to $\pm 25^0$.
- Above gas temperatures of around 1300K total pressure probes are not normally viable, as they will require cooling and hence become so large that associated pressure drops are prohibitive.
- Coverage requirements depend on how well understood the pressure uniformity is at a station, and should be agreed with the relevant component designer.
- Many radial and circumferential locations may be addressed via either multiple heads on vane leading edges, or several multihead rakes inserted into the gas stream.

Differential pressures:

- Normally pressure is measured as the difference between the gas stream and ambient, and an absolute pressure level obtained by addition of ambient pressure to the gauge reading.
- To read a pressure difference between two points, both sides of a transducer may be connected to tappings at the engine stations in question. This allows use of a more precise, lower range transducer, and avoids large inaccuracies due to the subtraction of similar numbers.
- One disadvantage is that recalibrating such a transducer is not possible without disconnecting the instrumentation, unlike for scanivalve systems.

Transient pressures:

- For transient testing dedicated pressure transducers, designed to optimize transient response, are required for each tapping. This provides a continuous reading, unlike a scanivalve system.

- The transducers are mounted local to the engine to minimize line volumes, and hence allow fast response to pressure changes; they may be water jacketed to enhance thermal stability.
- Line length limits are around 5m for ordinary handling and 1m for faster transients such as fuel spiking. In the former case a divertor valve may be employed to allow the same tapping to be read by the steady state scanivalve; for the shorter line length space does not permit this. Typical scan rates range from 10 to 500 scans per second.
- Absolute accuracies are lower for dedicated transient transducers than for a scanivalve system, around 1.5% of full range, and the transducers are more subject to drift.
- A calibration curve should be run at the start of each working day to provide a comparison with the steady state instrumentation. In addition a transient manoeuvre should be performed to check for lag due to divertor valve faults.

Dynamic measurements of pressures:

- Dynamic measurements of pressure address high frequency pressure perturbations, rather than 'dynamic pressure' as in 'velocity head'.
- These measurements are employed to detect flow instabilities such as rotating stall or rumble which can occur in the compression and combustion systems.
- The accuracy in determining amplitude is low, around 10% of range, as the design is optimized for response and the thermal environment is normally uncontrolled.
- Probes such as the kistler (resistive) and kulite (piezo) varieties are utilised, which incorporate pressure transducers – the low volume allows response to the very high frequencies involved.

5.27.2 Temperatures

Measurement of temperatures provides the following information on engine and component performance.

- Determination of overall engine performance requires inlet temperature so that parameters can be referred back to standard conditions.
- The temperatures local to a component are required to define its performance, i.e. efficiency and flow capacity.
- Temperatures are required to ensure the engine is not operated beyond limits stipulated for mechanical integrity.

- Mass flow measurement utilizes temperature levels.

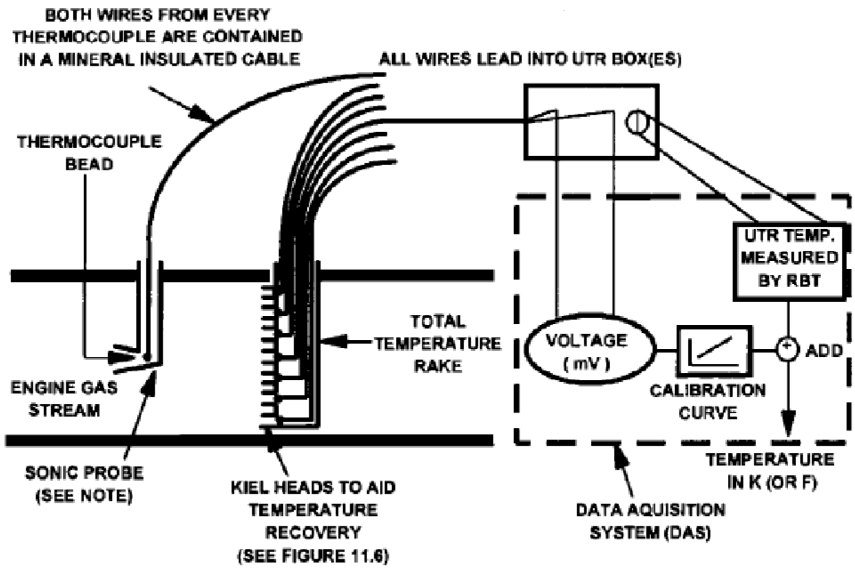


Fig: Temperature measuring system

Resistance bulbs thermometers (RBT):

- Here temperature is measured via changes in the resistance of a heated material. Platinum is frequently used, hence the common alternative expression PRT (platinum resistance thermometer).
- In theory resistance thermometers are suitable for temperatures up to around 1000 K, and may give a high accuracy of potentially around 0.1K if carefully calibrated.
- They are however comparatively delicate, and rarely used actually within an engine;

Snakes:

- Snakes are resistance thermometers many metres long sometimes used to measure average inlet temperature, and may for example be strung out over the inlet debris guard or splitter.
- One disadvantage is that the large physical size makes accurate calibration impossible, hence a preferred alternative is multiple resistance bulbs.
- Indicative overall accuracy for a snake is 1–2 K.

Thermocouples:

- If two dissimilar metal wires are connected at a junction, and the loose ends maintained at some reference temperature, a voltage is generated dependent on the temperature difference between the junction and the reference.

- Typically the junction is a welded bead of up to 1.1 times the wire diameter.
- Thermocouples are less accurate than RBTs, but more robust. The loose ends' temperature is maintained by either a UTR (uniform temperature reference) box, whose own temperature is measured by resistance bulb thermometers, or an Icell (ice cell).
- Single pieces of wire should be used between the hot and cold ends, otherwise measurement uncertainties increase by around 2K per extra junction.
- With single pieces batch wire calibration is applicable, where a calibration is obtained of a number of thermocouples made from a particular batch of cable.
- Providing the results agree, this calibration is applicable to other thermocouples made from that same batch.
- In siting thermocouples radiation from adjacent surfaces must be avoided, otherwise the temperature measured is not that of the gas stream.
- For locations where radiation may be severe, shielded thermocouples are employed, which use up to four concentric thin tubes surrounding the thermocouple bead.

The application of the above devices to measuring temperatures at key engine stations is described below:

Air inlet temperature:

- Recommended coverage is at least 3 RBTs mounted on the intake debris guard, and more if non-uniform inlet temperature profiles are suspected.
- The test bed layout should be adjusted to ensure that the difference between the readings is less than 1K, otherwise it is difficult to be sure that the true average temperature is being measured, and the temperature profile may fundamentally affect engine performance.
- Snakes or even thermocouples may also be used, however this results in lower accuracy as described above.

Cold end (compressor) temperatures:

- Usually thermocouples are employed, and accuracy is as described above. Coverage should be at least three points circumferentially, with rakes having one to five heads radially depending on engine size and the expected radial temperature profile.

- The heads are usually placed on centres of equal area to provide uniform coverage and assist in data averaging.
- An aero-engine fan is a special case; due to the temperature profiles and relatively low temperature levels rakes with up to ten heads are employed.

Hot end (turbine) temperatures:

- Temperature measurement is significantly more difficult for turbines, for two main reasons:
  - Above temperatures of around 1300 K, the mechanical integrity of a probe becomes an issue, requiring bulky, cooled designs which are highly intrusive. Such measurements are rarely attempted.
  - At combustor exit, and to a decreasing extent rearwards through a turbine system, there is severe temperature 'patternation' causing both circumferential and radial profiles. This is due to having discrete fuel injection points within the combustion system and cooling air influx downstream. To obtain a thermodynamically valid average temperature from a finite number of readings may be impractical.
- For both reasons the temperature at combustor exit cannot be measured, and measurements are rarely possible at exit from any first HP turbine stage.
- For measurement stations further downstream, the minimum coverage required is at least eight locations circumferentially, and three to five thermocouple heads radially, depending on engine size.
- Patternation introduces a further error beyond the thermocouple inaccuracies described above. Rather than using centres of equal area, head placement is often biased towards the walls, where the temperature gradient is steepest.

Transient temperatures:

- One further important thermocouple property is response time. Physically large thermocouples take time to respond to temperature changes, due to thermal inertia, and are unsuitable for transient development testing.
- Response is governed mainly by the time constant of the junction itself. For development testing physically small junctions are employed, mounted to minimise conduction and radiation.

- For control system instruments, large robust ‘production’ devices are required. Here the time constant of the thermocouple can be allowed for in the control algorithms, or heat transfer increased by increasing the flow past the thermocouple junction. Where the pressure ratio to ambient exceeds around 1.2 a sonic probe is used.
- A small flow is extracted from the gas path through a venturi surrounding the thermocouple bead. The flow accelerates to choked conditions at the bead and then diffuses before being dumped overboard. Otherwise aspiration is employed, where higher pressure air is injected to draw flow past the bead by an ejector effect.

5.27.3 Thrust

- For aero-engines, measuring thrust is essential for three main reasons:
  - This is a vitally important, fundamental design goal and will determine whether or not the engine/airframe combination can meet the desired mission.
  - It is required to calculate SFC.
  - Any inferred component lifing information requires a thrust level to be meaningful.
- An engine is mounted in a cradle and restrained axially via load cells, which measure the axial force required. These contain springs and are often preloaded and mounted in opposition to maintain stiffness. Standard practice is to calibrate before and after a test run, often by hanging weights, and use the mean as valid during the test.
- An indicative accuracy level for the load cell is within 0.25% reading; to convert this to thrust requires test bed calibration. Basically, for indoor test beds the impact of the static pressure field on the engine relative to that in an infinite atmosphere must also be evaluated.
- This leads to an overall thrust accuracy of around 1%.
- In an altitude chamber additional effects contribute to measured thrust, the inlet ducting incorporates a slip joint to prevent axial force transmission to the engine; this joint has a seal area larger than the upstream duct.
- The actual gross thrust produced by the engine is the measured load cell force plus inlet momentum drag and pressure loads acting on the duct and seal areas.
- Typical accuracy is around 1.5%. For both test beds, measurement of mass flow is also important, to corroborate predictions of momentum drag at flight conditions.

5.27.4 Shaft speeds

Shaft speed measurements provide valuable component information:

- Anticipated turbomachinery performance is strongly influenced by speed, especially for compressors.
- Turbine lives and shaft critical speeds are crucially dependent on speed, and for aero engines shaft speed levels are a certification issue.
- For shaft power engines output speed is of vital importance, and is also used in the calculation of output power.

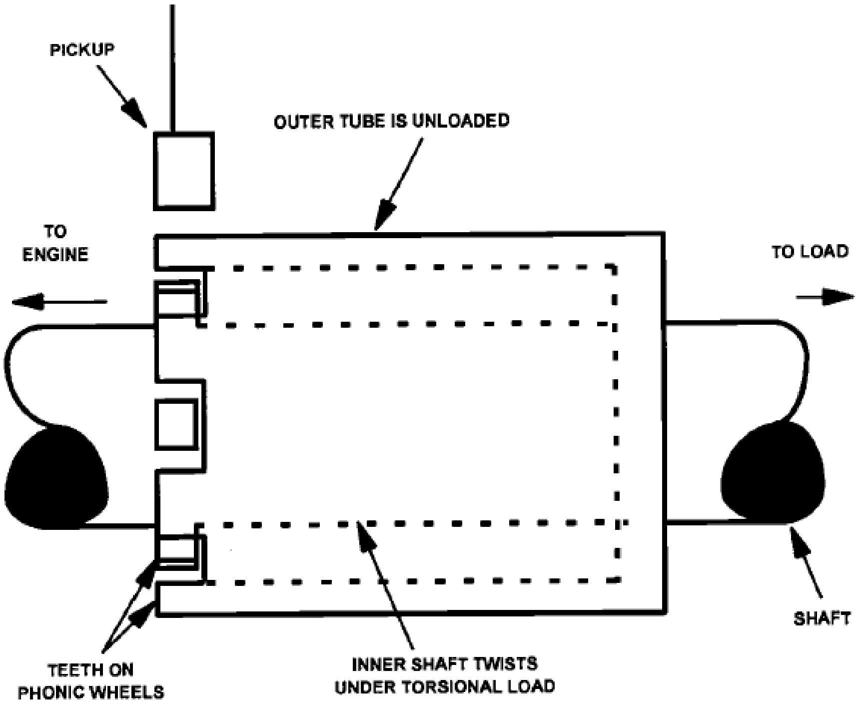
A phonic wheel and pick up are normally used. This method is highly accurate and reliable, and hence available even as a production measurement. The passing of teeth cut in a wheel, integral with the shaft, is sensed by an electromagnetic coil. The pulses generated are converted to a shaft speed, knowing the number of pulses per revolution.

Two main methods may be used for this:

- A clock and pulse counter suits steady state operation, and as implied counts the number of pulses over a timed period. Accuracy is around 0.1%, assuming engine operation is stable.
- A frequency to DC converter suits transient operation, and gives an readout of instantaneous shaft speed. Again accuracy is around 0.1%.

5.27.5 Engine output shaft torque and power

- These are highly interrelated as power is simply the product of torque and rotational speed. A torquemeter forms part of a load carrying shaft, and measures torque by sensing the relative rotation of two ends of a length of shaft. Shaft torque must be measured at an appropriate point along the output shafting, to exclude any losses which are not part of the engine supply.
- Figure 11.10 illustrates one method where phonic wheels, which also measure speed, are attached to both the shaft and an outer unloaded tube.
- By this means the teeth are in the same plane, and changes in the waveform picked up indicate angular displacement, and hence torque.
- Overall torquemeter accuracy is around 0.5–1%, depending on engine stability.
- An alternative method utilises strain gauges to measure shaft twist, however such devices are delicate and have not been widely successful.



Notes:
Twist of inner shaft changes angular relationship of phonic wheels.
Changes in pickup waveform allow computation of shaft torque.
The type illustrated is known as a 'phase displacement meter'.

Fig. 11.10 Shaft torque measurement.

- A hydraulic dynamometer may also measure torque. Input torque is transmitted to the casing by the water and any bearing friction; the casing is freely mounted externally on bearings to allow torque measurement via a load arm and a weighing system.

5.27.6 Vibration

- Current engine test cell systems were designed to perform a simple vibration amplitude check.
- If the root mean square (RMS) vibration amplitude falls within specifications under programmed operating conditions with no need for adjustments, then the engine is considered to be ready for installation.
- Engine test cell vibration analysis techniques are being developed to improve engine reliability and availability while simultaneously reducing life cycle costs.
- The engine test cell vibration diagnostic system under development provides both real-time and post-test analysis of engine vibration data.

- The real-time vibration diagnostic system identifies sensor faults before they lead to an incorrect diagnosis and plots key vibration diagnostic features such as tracked orders during the test.
- Vibration sensor faults are a common cause of test cell ineffectiveness.

5.28 Data Acquisition System for Gas turbine engine

- A commercial data acquisition system is adopted to the gas turbine engine test cell at TEI. The new data acquisition system is set to work to measure and record partial testing data of the gas turbine engine.
- There are about 200 parameters which need to be scanned automatically through the data acquisition system in the test cell of such a complicated jet engine.
- However due to the limited number of channels of the new data acquisition system it was concentrated only on 15 most important parameters of the gas turbine engine.
- The selected parameters are measured and recorded continuously. These parameters are given in Table III. For the partial data acquisition of gas turbine engine the following hardware is used:
    - Personal Computer
    - Data Acquisition System comprising of ;
        - Multimeter installed internally
        - Multiplexer
    - Different types of cables, thermocouples and connectors.
- Same signals which are coming from the test engine to the existing data acquisition system are used for the new data acquisition system.
- Some signals are taken directly coming from the engine monitoring system processor (EMSP) which is a part of the control system of the engine. The engine has some sensors of his own in order to control itself and the signals that are measured are directly coming from these sensors through the EMSP.
- All channels of the data acquisition system were grounded appropriately and the overall calibration or check is done to maintain the confidence in its accuracy and to avoid the collection of faulty data.
- Calibration is, in a way, checking and controlling of the route from measuring device or transducer to computer through the data acquisition system by applying prescribed inputs to the measuring system to see the expected value in the range of acceptable limits.

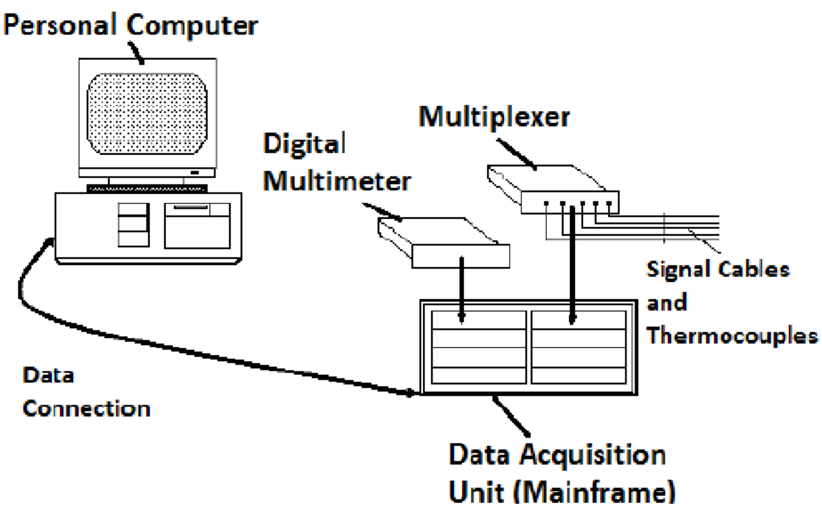


Fig. 2. *Simple sketch of data acquisition system*

TABLE III. MEASURED PARAMETERS OF TURBOFAN ENGINE

Parameter Name	Description
A8	Exhaust nozzle area (%)
AUG	Augmenter fuel valve ratio
APLA	Aircraft power lever angle (deg)
CDP-CBP	Compressor discharge and bleed pressure difference (kPa)
DPP	Fan duct pressure ratio
EPLA	Engine power lever angle (deg)
IGV	Fan inlet guide vanes (deg)
NF	Fan speed (% rpm)
NG	Core (or compressor) speed (% rpm)
Mach	Simulated flight Mach number
T2	Fan inlet temperature (K)
T56	Exhaust gas temperature (K)
Thrust	Observed thrust (kN)
VIBC	Vibration of compressor at turbine frame (mils)
VIBF	Vibration of fan at turbine frame (mils)

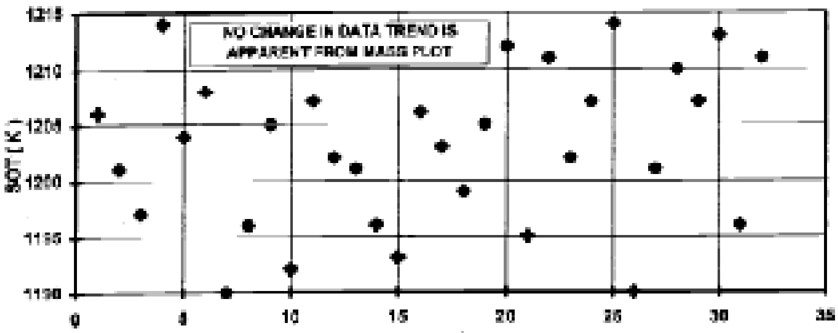
5.29 Engine performance trends: Mass and CUSUM plots

Changes in component manufacture or build practice may cause increasing numbers of engines to fail the pass off test. Identifying these changes early amongst the general scatter is challenging. Though some special instrumentation may be fitted for the pass off test, more modern practice is to rely on that of the production control system.

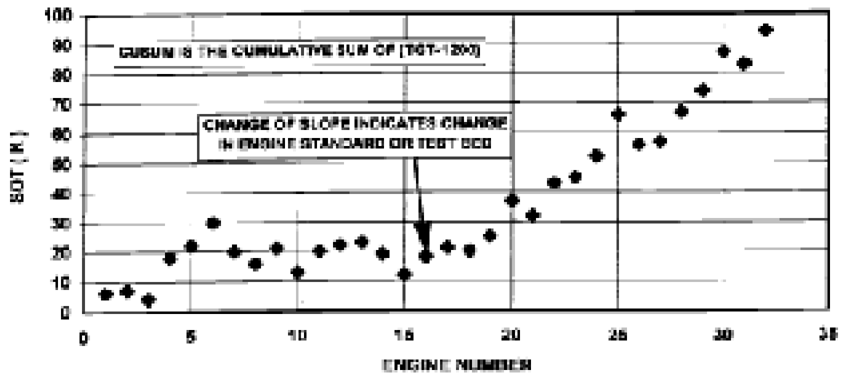
Instrumentation is therefore often too sparse or inaccurate to suit the conventional analysis methods. Though these may be employed additional methods are necessary, which emphasize comparison with other engines. Figure 11.11 shows an example where pass off data from a production run is plotted for LP turbine inlet temperature:

Engine no. (–)	SOT (K)	SOT-1200 (K)	CUSUM (K)	Engine no. (–)	SOT (K)	SOT-1200 (K)	CUSUM (K)
1	1206	6	6	17	1203	3	21
2	1201	1	7	18	1199	−1	20
3	1197	−3	4	19	1205	5	25
4	1214	14	18	20	1212	12	37
5	1204	4	22	21	1195	−5	32
6	1208	8	30	22	1211	11	43
7	1190	−10	20	23	1202	2	45
8	1196	−4	16	24	1207	7	52
9	1205	5	21	25	1214	14	66
10	1192	−8	13	26	1190	−10	56
11	1207	7	20	27	1201	1	57
12	1202	2	22	28	1210	10	67
13	1201	1	23	29	1207	7	74
14	1196	−4	19	30	1213	13	87
15	1193	−7	12	31	1196	−4	83
16	1206	6	18	32	1211	11	94

(a) Tabular test data and CUSUM



(b) Mass plot: SOT versus engine number



(c) CUSUM plot: SOT versus engine number

Fig. 11.11 Test data trending: 'mass' and CUSUM plots.

- ***Mass plots:***
    - These show pass off performance parameters of interest plotted versus engine number over a time period.
    - They truly define mean engine performance and scatter, and are useful for detecting measurement errors and ‘rogue’ engines.
- ***CUSUM plots:***
    - CUSUM - Cumulative sum
    - These plot the cumulative sum of the difference between each engine’s temperature (say) and an arbitrary value within its scatter band, versus engine number.
    - Changes of slope of the mean line indicate changes of trend that may be almost impossible to detect from the mass plot.

5.30 Accuracy and Uncertainty in Measurements

5.30.1 Accuracy

- Accuracy is the closeness of agreement between a measured value and the true value.
- There are some definitions available for ‘accurate measurement’ in the ISO vocabulary of metrology terms. According to them, a ‘measurand’ is the specific quantity to be measured and the ‘accuracy of measurement’ is defined as the closeness of agreement between the outcome of a measurement and the actual value of the measurand.
- Since the true value is unknowable, it may be logically not possible to quantify the accuracy of a particular measurement. Hence, in the ISO vocabulary of terms in metrology, it also mentioned that ‘accuracy is a qualitative concept.’
- The definition of accuracy presents a logical problem. To simplify the problem and concentrate on other issues, the terms ‘accuracy’ and ‘uncertainty’ could be considered as synonyms, at least for optical measurements.
- According to ‘Gage maker’s rule,’ the test instrument must be 10x more accurate when compared to the tolerance. Hence it is a challenge to establish the accuracy of a tool, especially if it is a complex tool.

5.30.2 Uncertainty

- According to the definition outlined in the ISO vocabulary of terms in metrology, the 'uncertainty of a measurement' is a 'parameter, related to the outcome of a measurement, characterizes the dispersion of the values that could logically be attributed to the measurand.'
- Uncertainty is related to a specific measurement of a particular component. Although the instrument plays a part in the uncertainty of a measurement, the uncertainty is not attributed to the instrument utilized.
- Uncertainty is not just the measurand's standard deviation, but also takes into account estimates of all contributions to the dispersion of values that might logically be attributed to the measurand.
- The 'Guide to the Expression of Uncertainty in Measurement' defines Type A uncertainties are those which the metrologist selects to treat by statistical techniques, and Type B uncertainties are those treated by other aspects such as the judgment of the metrologist, analysis, handbook values, and much more.
- None of these techniques is neither wrong nor superior to the others. A typical problem in optical measurement is defined by different phrases including 'uncertainty in the realization of the measurand,' 'uncertainty in the definition of the measurand,' and 'measurement divergence.'
- Uncertainty in the outcome of a measurement may crop up from a partial definition of the measurand, considering the characteristics of the components submitted to test.
- Agreement or disagreement between measurements performed on various instruments can be assessed in the perspective of the uncertainties of the measurements.
- The 'Guide to the Expression of Uncertainty in Measurement' presents the methodology for estimating uncertainty. The objective is to provide a good evaluation of the uncertainty on the basis of data of the measurement process. Although a comprehensive model is not needed, understanding the key contributors to the uncertainty is required.

5.31 Uncertainty analysis

The U.S. national standard we use at NREL for uncertainty analysis.

Step 1:

Clearly define the "true value" sought, in writing. It is well worth the time to do this in writing, for it will keep before you what you are trying to measure and will help clarify the measurement process and the experiment goal.

Step 2:

List every possible elemental source of measurement error that can be thought of, no matter what the source or how large or small the error may be thought to be.

Step 3:

Group the error into these three categories, by source:

(1) calibration errors;

(2) installation and data acquisition errors; and

(3) data reduction errors.

Calibration errors are those associated with the calibration of each measuring instrument, sensor, transducer, etc. Installation errors are those errors that arise from how sensors are installed for the experiment. Data acquisition errors are those associated with the performance of the data acquisition system (including sensors) in the environment in which it is used.

Step 4:

Classify the errors into systematic and random errors. If data exist from which a standard deviation can be calculated, consider it a random error. Manufacturer's specifications can give useful information for the pre-test analysis. Random errors produce scatter in the final result. Otherwise, consider the errors to be systematic errors.

Step 5:

Separately propagate the two types of error to the final result Use the Taylor series or small deltas ("dithering") to determine the sensitivity of the final result to each individual source of error. Simply adding the errors may lead to an uncertainty estimate that is too large or too small, depending on the sensitivity coefficients for each error.

Step 6:

Calculate the uncertainty interval using either model (or both).

Step 7:

Use pretest and post test analyses. The use of both tests reduces the cost and risk of performing useless experiments, publishing invalid data, drawing wrong conclusions, or making wrong decisions. Uncertainty analysis should be factored into decisions, such as those concerning awards for PV cell, module, or system performance.

Step 8:

In the final report, show the final random error component of the uncertainty together with the associated degrees of freedom, the bias limit, and the uncertainty model used.

5.32 Performance Reduction Methodology

5.32.1 Physical Faults

It is useful to examine a number of physical faults that may exist in the gas path of the gas turbine, affecting seriously the component and therefore the overall performance of the engine. The physical faults presented in Table 1 and discussed in details.

Fouling:

Fouling is one of the commonest causes of performance reduction encountered by users of gas turbines and can count for more than 70% of the performance loss during operation. Particular contaminants (dirt, dust, oil, pollen, salt etc.) have the tendency to stick to the airfoil surface and change the aerofoil inlet angle, aerofoil shape, increase surface roughness and narrowing airfoil throat aperture [2], causing the degradation of gas path components' pumping capacity and efficiency. The decrease in mass flow will result in a decrease in thrust necessitating an increase in the rotational speed to maintain a required thrust level, while the decrease in isentropic efficiency will cause an increase in TET and SFC, thereby reducing the engine life and increasing the engine operating costs.

Performance deterioration due to fouling is recoverable by cleaning/washing; when the mass flow decreases by approximately 2.5%.

Corrosion:

The chemical reaction between flow path components and contaminants that enters the gas turbine with the inlet air, fuel or injected water/stream, causes corrosion that is the loss of material from those gas path components. Turbine blades are more susceptible to corrosion due to the presence of combustion products and elevated temperatures. The effect of corrosion is quite similar to the effect of erosion, since there is a loss of material, increase of surface roughness that leads to reduction of the component performance and isentropic efficiency. An effective protection from corrosion attack and subsequent loss of performance for both compressor and turbine is through coating.

Erosion:

Operators flying in sandy or dusty environments suffer from the phenomenon of erosion. Most of the ingested dust particles in a desert environment are found to have sizes of 0-1000 μm. Erosion is caused by, the abrasive removal of material from the gas path components by hard particles suspended in the air stream. Erosion leads to increased blade surface roughness, blade tip, seal clearance and changes in the inlet metal angle, airfoil profile, throat opening and blade surface pressure distribution. In compressors due to pressure loss, there is drop of mass flow capacity and component efficiency. In turbines there is a drop in efficiency but due to larger passing area, flow capacity increases and less back pressure produced on the compressor. In contrast to the case of fouling erosion is non-recoverable by washing or cleaning.

FOD:

FOD is the result of a body striking the internal surfaces of the gas path components of the gas turbine. The origin of such particles can be via fan section, with air or broken particles from the engine inside being carried downstream. A small dent or nick to the leading edge of attacked blades can cause a stress concentration that may develop into a fatigue crack and threaten the integrity of the blades and therefore the whole engine. The impact of larger object damage increases the throat area, altering the surface roughness and resulting reduction in both flow capacity and efficiency.

Air leakage:

Air leakage on gas turbines refers to the leak of a duct or other mechanical containment of the engine (e.g. compressor), to the outer environment.

Rubbing wear:

Rubbing wear is the removal of material from the rotor blade tips and knife edges seal, due to contact between static and rotating parts that happens in both compressors and turbines.

Hot end component damage:

The very high temperatures in turbines can eventually cause damage at the trailing edges of the NGVs and rotor blades, because these parts are thin and difficult to cool.

Labyrinth seal damage:

The damage to the seals e.g. due to aging, increases the internal leakage between the discharge and suction side of the compressors and turbines.

Increase tip clearance:

Typical reason for the increased tip clearance is the thermal expansion. This effect can be accentuated by casing and shaft distortion, which is susceptible to high G loadings during combat flight maneuvers, as well as to turbulence and heavy landings.

Seal erosion:

Any wear in the seals results in localized heating and an increase in compressor bleed air.

Table 1. Effect of physical faults on components' performance

Physical	Effect on Component Performance	
Fouling	Drop in compressor and turbine flow capacity	0.0 – [-5.0%]
	Drop in compressor and turbine efficiency	0.0 – [-2.5%]
Corrosion	Drop in compressor flow capacity	0.0 – [-5.0%]
	Rise in turbine flow capacity	0.0 – [+5.0%]
	Drop in compressor and turbine efficiency	0.0 – [-2.5%]
Erosion	Drop in compressor flow capacity	0.0 – [-5.0%]
	Rise in turbine flow capacity	0.0 – [+5.0%]
	Drop in compressor and turbine efficiency	0.0 – [-2.5%]
FOD/DOD	Drop in compressor and turbine efficiency	0.0 – (-5.0%)

5.32.2 Diagnostic Methods

Gas Path Analysis (GPA)

Gas Path Analysis (GPA) pioneered by Urban, is used to assess the condition of individual engine components based, on the aero-thermodynamic relationships that exist between the component and direct measurements of gas path parameters. The theory behind this relationship is shown in the conceptual framework in Fig.1 which can be summarised by: The presence of a primary gas-path physical fault induces change in the component characteristic that shows up a deviation of the measurable parameters from the baseline conditions. Therefore, the purpose of the GPA is to detect, isolate and quantify the gas path components faults that have observable impacts on the measurable variables with the hope that will facilitate the subsequent isolation of the underlying physical fault.

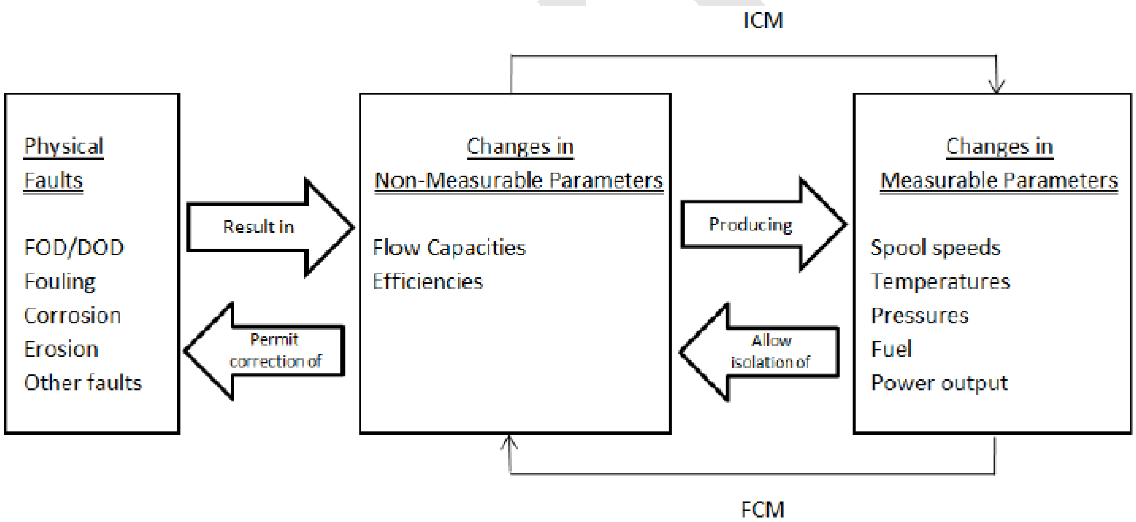


Fig. 1. GPA Principle Engine

Kalman Filters

In 1960, Kalman published a recursive solution to the discrete data linear filtering problem and in 1961, Kalman and Bucy followed up a paper on the continuoustime version. The filter was finally called the Kalman Filter, although Shet and Rao argued that it is an algorithm rather than a filter. Kalman Filter (KF) is an optimal recursive data processing algorithm, used in order to provide an estimation of the health of the engine components in presence of measurement noise and sensor bias. A KF processes all available measurement data regardless oftheir precision, plus prior knowledge about the system and measuring devices, to produce an estimate of the desired variables in such a manner that the error is minimized statistically. After a run of a number of candidate filters many times for the same application, the average results of the KF would be better than the average results of any other.

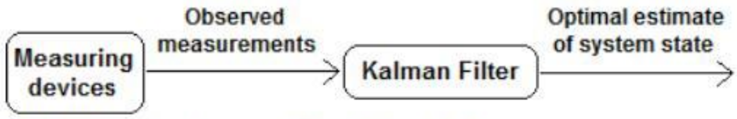


Fig. 4. Typical application of the Kalman Filter

Genetic Algorithms

First pioneered by H.J Holland in the 1960 at University of Michigan, Genetic Algorithms (GA) has been widely studied, experimented and applied in many engineering fields. The basic concept of GA is designed to simulate processes in natural system necessary for evolution, specifically those that follow the principles first laid down by Charles Darwin of survival of the fittest. The GAs is applied as an effective optimization tool to obtain a set of components parameters that produce a set of predicted dependent parameters, through a non-linear gas turbine model that leads to predictions which best match the measurements. The solution is obtained when an objective function which is a measure of difference between predicted and measured parameters, achieves its minimum value.

A diagnostic algorithm based on GA is implemented as a computer simulation in which a population of abstract representations (called as genome or the genotype or chromosomes) to an optimisation problem fitness is associated to the value of one.

$$Fitness = \frac{1}{1+OF} \qquad (3)$$

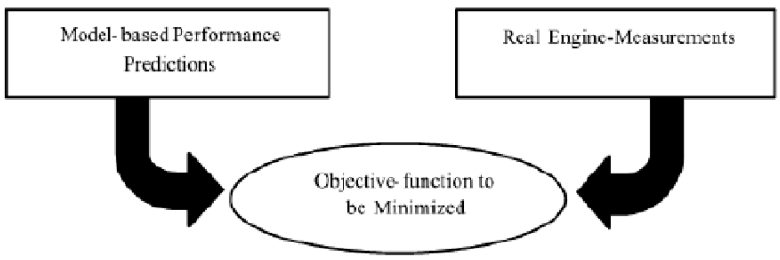


Fig. 5. The objective function [48]

Previous exam questions:
1. (10AE74 - Dec. 2017/Jan. 2018)
a. What do you mean by structural integrity in gas turbine engines? (7M)
b. Explain the testing of inlet distortion and surge test. (6M)
c. Explain with neat sketch the working of indoor air testing. (7M)

d. What do you mean by test cell? What are the factors considered for design of test engine test beds? Explain. (10M)

e. What is data acquisition system? How does it help in the engine testing and design factors analysis? (5M)

f. Explain the following: (5M)

i. Uncertainty analysis in engine testing

ii. Explain the typical MASS and CUSUM plots of engine testing.

2. (10AE74 - Dec. 2016/Jan. 2017)

a. Explain about altitude test facility (ATF) and write its uses. (7M)

b. Define engine trimming. (3M)

c. What is meant by test bed calibration? Write the steps involved in it. (6M)

d. Explain about the measurement of Thrust and Shaft speed. (10M)

e. Why do you want to measure pressure? List various pressures measuring devices. (4M)

3. (10AE74 - Dec. 2015/Jan. 2016)

a. Explain engine trimming process for various engines. (10M)

b. What are the basic engine ratings for turbojet and turbo fan? Explain briefly. (10M)

c. What do you mean by test bed? Give their types and explain briefly any two of them.(10M)

d. Write a short note on following: (10M)

i. Pressure measurements

ii. Temperature measurement

4. (10AE74 - Dec. 2014/Jan. 2015)

a. With a neat sketch, explain outdoor sea level thrust test bed. (10M)

b. Explain briefly durability tests in aircraft engine. (10M)

c. Write short note on testing is done in a test cell to measure the following operating parameters in aircraft engine (12M)

i. Temperature ii. Pressure

d. Briefly discuss the Mass and CUSUM plots. (8M)

5. (10AE74 - Dec. 2013/Jan. 2014)

a. Classify the testing of engine based on performance and quality validation. (8M)

b. With a neat sketch, explain outdoor sea level thrust test bed. (12M)

c. Explain the different technique of pressure measurement in an engine. (12M)

d. What do you mean by test bed? Give their classification based on their configuration.(8M)

6. (6AE74 – December 2012)

a. Explain the following engine testings: (10M)

i. Altitude test facility (ATF)

ii. Flying test bed.

b. Discuss various preliminary flight rating tests. (10M)

c. Why do we need test bed calibration? What are all the steps involved in it? (8M)

d. What are all the reasons for measuring pressure in test beds? Describe the pressure gages of test bed instrumentation. (12M)

7. (6AE74 – December 2011)

a. Explain: i. Open air test bed; ii. Flying test bed. (6M)

b. Explain the preliminary flight rating test. (6M)

c. Explain the ground testing of engine installed in aircraft. (8M)

d. Write briefly the instruments used in test cell for measurements (12M)

8. (6AE74 – June/July 2011)

a. What are methods for inlet flow distortion modeling? (15M)

b. What are methods for initiating surge in compressors? (5M)

c. Explain instrumentation system for measurement of temperature of turbine blading?(15M)

9. (6AE74 – Dec. 2009/Jan. 2010)

a. Explain the engine trimming process. How it is carried out on different engines? (10M) b. What are the measurements of temperature gages and pressure gages of test cell instrumentation? (10M)

c. What is bell mouth inlet and screen? With the help of a neat sketch, explain how it is helpful in various measurements? (10M)

10. (6AE74 – December 2010)

a. What are various preliminary flight rating tests? Explain. (10M)

b. Explain the following engine testing with simulated air0inlet distortion:

(10M) i. Distortion screen installed in the cylinder.

ii. Ducted-nozzle distortion technique.

c. What are the various uncertainties in measurements? (10M)

d. Explain typical data acquisition system. (10M)