Module - 3

ENGINE PERFORMANCE

Syllabus:

Design & off - design Performance. Surge margin requirements, surge margin stack up. Transient performance. Qualitative characteristics quantities. Transient working lines. Starting process & Wind milling of Engines. Thrust engine start envelope. Starting torque and speed requirements Calculations for design and off-design performance from given test data – (case study for a single shaft Jet Engine). Engine performance monitoring.

3.1 Design point and off design performance

The engine design point and design point performance

For initial definition work, the operating condition where an engine will spend most time has been traditionally chosen as the engine *design point*. For an industrial unit this would normally be ISO base load, or for an aero-engine cruise at altitude on an ISA day. Alternatively some important high power condition may be chosen. Either way, at the design point the engine configuration, component design and cycle parameters are optimized. The method used is the design point performance calculation. Each time input parameters are changed and this calculation procedure is repeated, the resulting change to the *engine design* requires *a different engine geometry, at the fixed operating condition*.

Off design performance

With the engine geometry fixed by the design point calculation, the performance at other key operating conditions can be evaluated, such as ISA SLS takeoff for an aero-engine. In this instance the calculation procedure is the off design performance calculation. Here *geometry is fixed and operating conditions are changing*.

3.2 Design point performance parameters

Engine performance parameters

A number of key parameters that define overall engine performance are utilized to assess the suitability of a given engine design to the application, or compare several possible engine designs.

- **Output power or net thrust:** It is evaluated via the overall cycle calculation. The term effective or equivalent power is used for turboprops and turboshafts, where any residual thrust in the exhaust is converted to power.
- **Exhaust gas power:** For a turboshaft engine core this is the output power that would be produced by a power turbine of 100% efficiency. It is of interest when engine cores are tested or supplied without their free power turbine.
- **Specific power or thrust:** This is the amount of output power or thrust per unit of mass flow entering the engine. It provides a good first-order indication of the engine weight, frontal area and volume.
- **Specific fuel consumption:** This is the mass of fuel burnt per unit time per unit of output power or thrust. It is important to minimize SFC for applications where the weight and/or cost of the fuel is significant versus the penalties of doing so.
- **Thermal efficiency for shaft power engines:** This is the engine power output divided by the rate of fuel energy input, usually expressed as a percentage.
- **Heat rate for shaft power cycles:** Heat rate is a parameter used only in the power generation industry, and is the rate of fuel energy input divided by the useful power output. Hence it is comparable to SFC but is independent of fuel calorific value.
- **Exhaust temperature:** For engines used in combined cycle for industrial power generation, high exhaust temperature is vital in maximizing overall efficiency. For combined heat and power the optimum value depends on the relative demand of heat versus power.
- **Exhaust mass flow:** For engines used in combined cycle or combined heat and power applications the exhaust mass flow is important in indicating the heat available in the gas turbine exhaust, and hence the overall plant thermal efficiency.
- **Thermal efficiency:** Thermal efficiency for aircraft thrust engines is defined as the rate of addition of kinetic energy to the air divided by the rate of fuel energy supplied, usually expressed as a percentage.

- **Propulsive efficiency:** Propulsive efficiency for aircraft thrust engines is defined as the useful propulsive power produced by the engine divided by the rate of kinetic energy addition to the air, again usually expressed as a percentage.

Cycle design parameters

This immediately show that the changes in pressure and temperature that the working fluid experiences strongly affect the engine performance parameters. The degree of change of pressure and temperature are reflected via the following cycle design parameters. Changes in component performance parameters have a secondary effect on the optimum values of engine *cycle design parameters*.

- **Overall pressure ratio:** This is total pressure at compressor delivery divided by that at the engine inlet.
- **Stator outlet temperature (SOT):** This is the temperature of the gas able to do work at entry to the first turbine rotor.
- **Fan pressure ratio:** This is the ratio of fan delivery total pressure to that at fan inlet, and is usually lower for the core stream than the bypass due to lower blade speed.
- **Bypass ratio:** This is the ratio of mass flow rate for the cold stream to that for the hot stream.

Component performance parameters

The plethora of parameters that define component performance in terms of efficiency, flow capacity, pressure loss, etc. As the level of component performance parameters improves, at fixed values of cycle design parameters, then the design point engine performance parameters also improve. Changes in component performance parameters have a secondary effect on the optimum values of engine cycle design parameters.

Mechanical design parameters

For a given performance design point to be practical the mechanical design parameters must be kept within the limits of the materials, manufacturing and production technology available. As a brief guide the major items to be considered are:

- Creep as a function of material type, metal temperatures, stress level or AN2
- Oxidation as a function of material and coating type, and metal temperatures

- Cyclic life (low cycle fatigue) as a function of material type and metal temperatures
- Disc and blade tensile stress as a function of rim speed or AN2
- Casing rupture as a function of compressor delivery pressure
- Choke or stall flutter as a function of fan or compressor referred speed
- Vibration (high cycle fatigue) of rotating components as a function of rotational speed and excitation parameters such as upstream blade numbers and pressure levels
- Shaft critical speeds

Life parameters

The two major life parameters are:

- Time between overhauls (TBO)
- Cyclic life (also called low cycle fatigue life): this is the number of times the engine is started, accelerated to full power, and eventually shut down, between overhauls.

The TBO is governed mainly by creep and oxidation life, while cyclic life is dictated by thermal stress levels. Typical life requirements for the major gas turbine applications are as follows.

Application	TBO (hours)	Cycles
Power generation – Base load	25 000–50 000	3000
Power generation – Standby/Peak lopping	25 000	10 000
Gas and oil pumping	25 000–100 000	5000–10 000
Automotive – Family saloon	5000	10 000
Automotive – Truck	10 000	5000–10 000
Marine – Military	5000–20 000	2000–3000
Marine – Fast ferry	5000–10 000	3000
Aero-engine – Civil	15 000	3000
Aero-engine – Military fighter*	25–3000	25–3000

*There is a large difference between past achievements and future targets, as the emphasis has moved from performance to cost of ownership.

Fuel type

Kerosene is the standard aviation fuel while marine engines burn diesel and most industrial applications use natural gas. The highly distilled forms of diesel used make little difference to performance compared with kerosene, but natural gas gives performance improvements because of the higher resulting specific heat of the combustion products.

3.3 Surge margin requirements and surge margin stack up

- Surge margin is defined by:

$$SM = 100 \times \frac{PR_{surge} \times PR_{working\ line}}{PR_{working\ line}}$$

- This is the internationally accepted SAE definition, though others have been used in previous years.
- The minimum steady state surge margin required will depend upon the engine configuration and application requirements.
- The power or thrust level at which the minimum surge margin occurs will also vary.
- During the engine concept design phase the steady state model can be used to predict surge margin 'pinch points'.
- For each engine application the worst operating conditions and transient requirements vary and it is not possible to cover all combinations here. Generally surge margin stack ups are conducted at these key operating conditions.
- Once the required margins there have been achieved, the values resulting at some other single operating condition may be compared for different engine types. This is usually at ISA sea level static, maximum rating.

The surge margin stack up

- The required surge margin is evaluated from a surge margin stack up where a range of issues, including transient working line excursions, must be addressed at the worst operating condition.
- These issues are listed below, together with typical values for a civil aero-engine HP compressor at ISA SLS and rated power or thrust.
- The required surge margin is calculated by adding *the arithmetic sum of the systematic deviances, to the root sum square of the random variances,* as per.
- For example:

New production engine to engine working line variation	0 ± 1.5%
New production engine to engine surge line variation	0 ± 4.0%
In service working line deterioration	–2.0%
In service surge line deterioration	–4.0%
Control system fuel metering, VIGV positioning, etc.	0 ± 1.0%
Reynolds number effects	–1.0%
Intake distortion	–1.0%
Transient allowance	–12.0%
Total	20% ± 4.4%
Surge margin required	24.4%

Typical surge margin requirements at ISA SLS (Sea-Level Static condition), maximum rating

- The required surge margin at ISA SLS and maximum rating varies greatly, being dependent upon accel and decel times required, engine configuration, whether centrifugal or axial compressors are applied, whether bleed valves or VSVs (variable stator vanes) are employed at part load, etc.
- The levels listed below are a first-order guide:

	Fan	LP/IP compressor	HP compressor
Power generation		15–20	15–20
Gas and oil		10–15	15–20
Automotive		15–20	20–25
Marine		10–15	15–20
Civil aero	10–15	15–20	20–25
Helicopter		15–20	20–25
Military fighter	15–20	20–25	25–30

- For a fan, the biggest single contributor to the requirement is inlet distortion where up to 5% surge margin must be allowed.

3.4 Transient Performance

Transient performance deals with the operating regime where *engine performance parameters are changing with time*. Engine operation during transient maneuvers is often referred to as *handling*.

3.5 Transient performance phenomena

Heat soakage:

- During transient operation there are significant net heat fluxes between the working fluid and the engine metal, unlike for steady state operation where there is negligible net heat transfer.
- For example, due to an accel from idle to full power or thrust the engine carcass must soak to a new higher steady state operating temperature, which absorbs typically 30% of the excess fuel energy.
- This net heat transfer from the working fluid to the metal is termed heat soakage and has a significant effect on engine performance.

- Where heat exchangers are employed the impact of heat soakage during transient operation can be dramatic, due to the large thermal inertias. Of conventional engine components the combustor has the largest effect, due to its large surface area, thermal mass and temperature changes.

Volume packing:

- During steady state operation the mass flow entering a given volume, such as a duct, is equal to that leaving.
- This is no longer true under transient operation as the pressure, temperature and hence density of the fluid change with time.
- This is known as volume packing and can have a notable impact upon an engine's transient performance, especially for the largest volumes such as ducts and heat exchangers.
- For most other engines the combustor has the largest volume and is the primary concern, though other components must also be considered for fast transients.

Tip clearance changes:

- During an accel the thermal growth of the compressor or turbine discs is slower than the pressure and thermal growth of casings, causing blade tip clearances to be temporarily increased.
- The converse is true during a decel which can lead to rubs. This change in compressor geometry affects its map, the main issue being lower surge lines. There is also a second-order reduction in flow and efficiency at a speed.

Heat transfer within multi-stage components:

- Where a single map is used to model a multi-stage component such as an axial flow compressor, net heat transfer will have a second-order effect upon the map during a transient.
- This is due to its effect upon gas temperature through the component and hence stage matching, as it changes the referred speed and hence flow capabilities of the rear stages.

Combustion delay:

- There is a time delay between the fuel leaving the injector and actually burning to release heat within the combustor.

- For steady state performance this is irrelevant, however for transient performance it should be considered.

Control system delays and lags:

- Hydro-mechanical components of the engine control system such as fuel valves, variable inlet guide vane (VIGV) actuation rings, etc. take a finite time to move to new positions demanded by the controller during a transient.
- This finite time may comprise a delay, where there is no movement for a given time, and/or a lag where the device is moving but lagging behind the demanded signal.
- In addition, control system sensors measuring parameters such as pressures and temperatures will show delays and lags relative to real engine conditions.

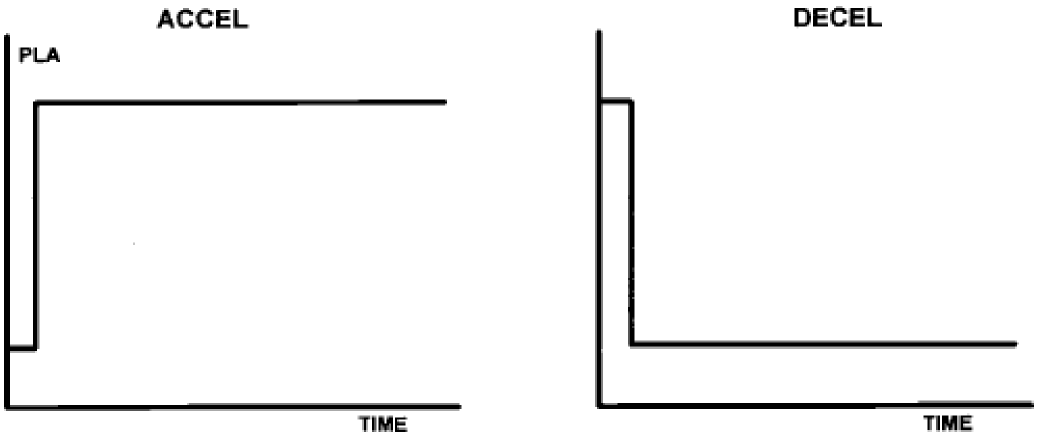
3.6 Transient Working Lines for Acceleration and Deceleration (Transient performance maneuvers)

Maneuvers comprise changes in engine power or thrust level, which the control system basically achieves by altering the levels of fuel flow.

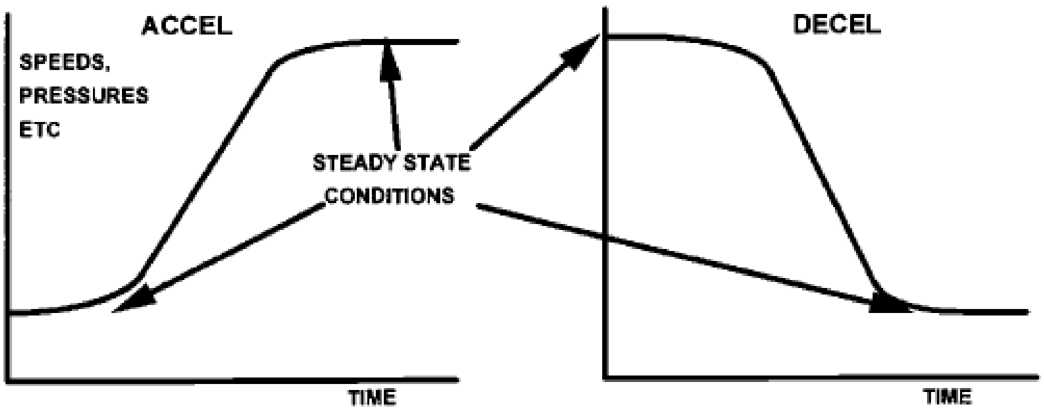
Slam accelerations and decelerations:

- Figure 8.1 shows the typical response versus time of gas generator performance parameters to a slam (step) increase, or decrease in power lever angle (PLA).
- In the simplest control system each level of PLA corresponds to a given speed demand. Following the step increase in PLA to initiate an accel (acceleration) the speed demand is far higher than the actual engine speed.
- The control system responds by increasing fuel flow at a defined limiting rate until the demanded speed is achieved. The over-fueling is typically between 20 and 100% of the steady state value for the current speed.
- Owing to the additional fuel flow the turbine produces more power than the compressor requires.
- For a decel (deceleration) the opposite occurs.
- The compressor working lines differ from steady state operation, as shown in Figs 8.2 and 8.3.
- The high temperatures associated with a slam accel are of such short duration that they do not affect the creep or oxidation life. However as transient times are reduced so is the cyclic life, due to the severe thermal stresses induced.

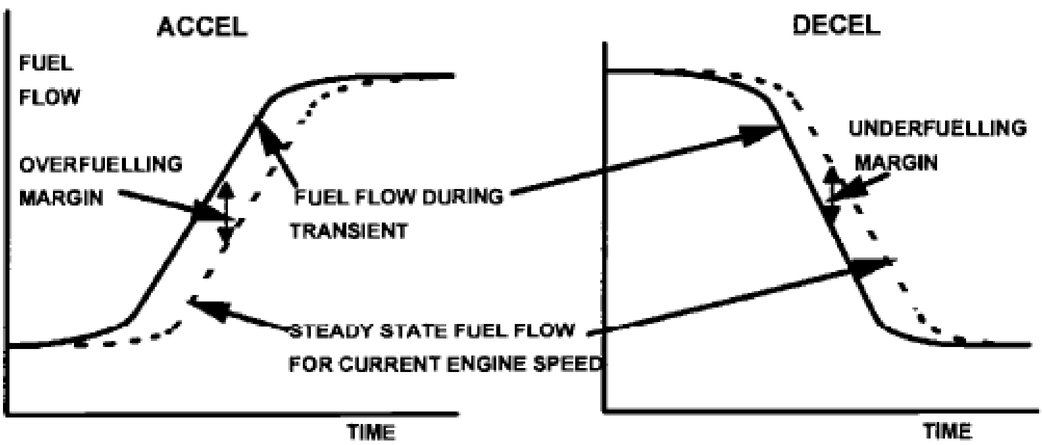
- One cycle is usually defined as a start, a holding period at idle, an accel to full thrust or power and eventually the corresponding engine shut down. Though the main damage is that from starting, fast accel times also contribute.



(a) Power lever angle versus time

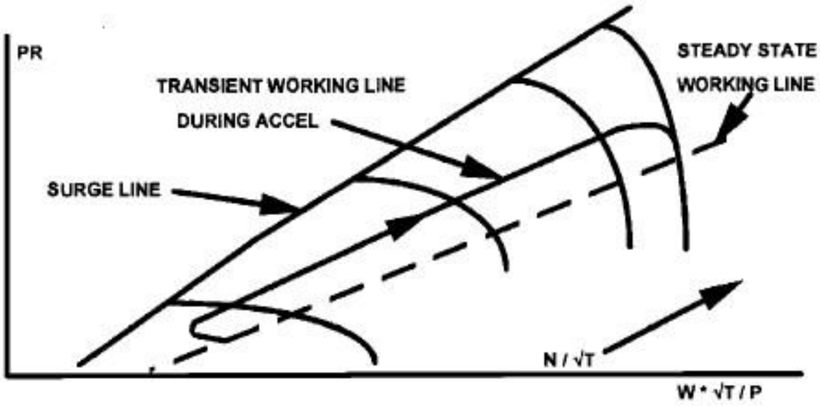


(b) Engine parameters versus time

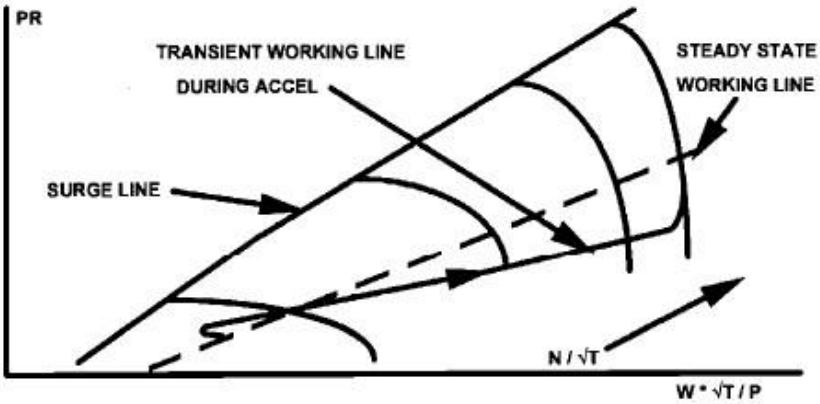


(c) Fuel flow versus time

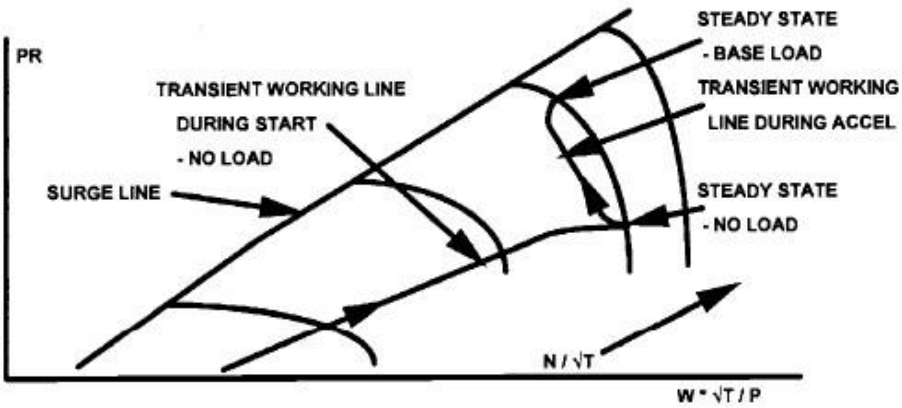
Fig. 8.1 Engine performance parameters versus time during slam accels and decels.



(a) HP compressor for turbojet, turbofan or free power turbine – one, two or three spool

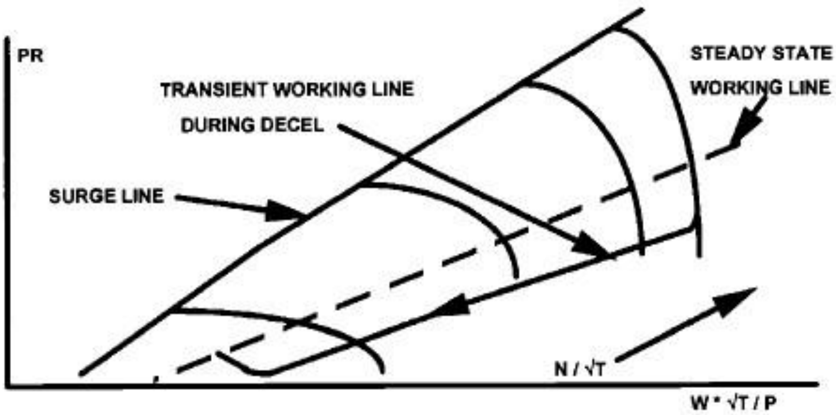


(b) LP or IP compressor, or fan, for turbojet, turbofan or free power turbine turboshaft/ turboprop – two or three spool

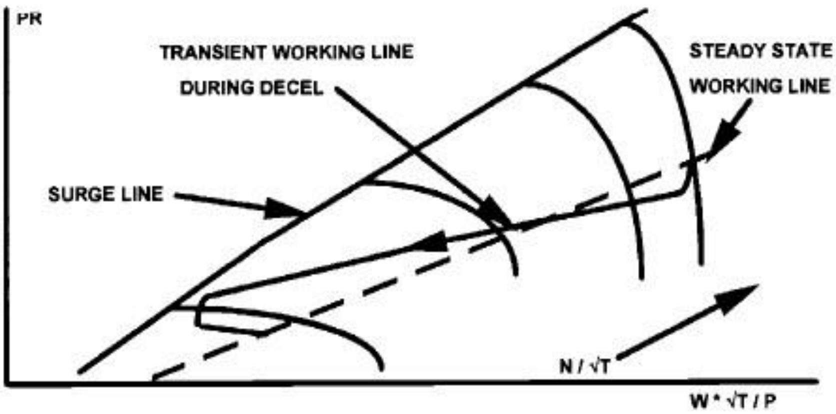


(c) Single spool turboshaft or turboprop with the load driven directly from the gas generator

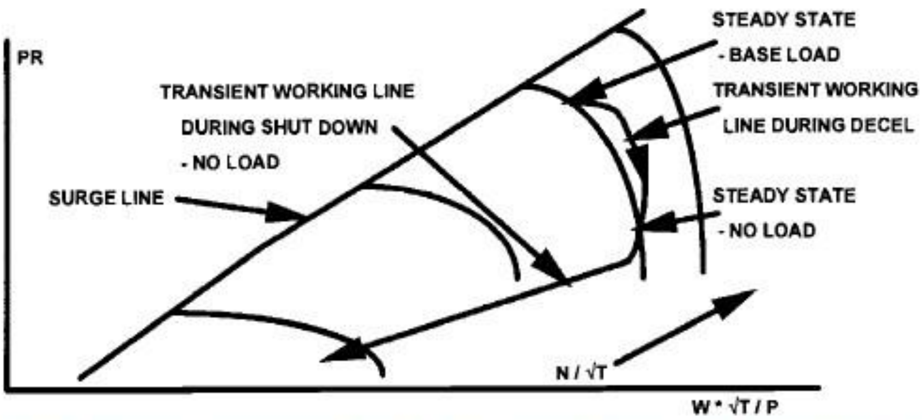
Fig. 8.2 Transient working lines during accel manoeuvre.



(a) HP compressor for turbojet, turbofan or free power turbine – one, two or three spool



(b) LP or IP compressor, or fan, for turbojet, turbofan or free power turbine turboshaft/ turboprop – two or three spool



(c) Single spool turboshaft or turboprop wth the load driven directly from the gas generator

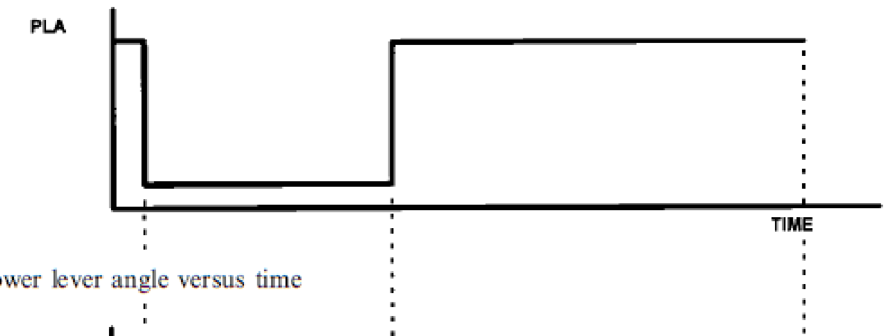
Fig. 8.3 Transient working lines during deceleration.

Slow accels and decels:

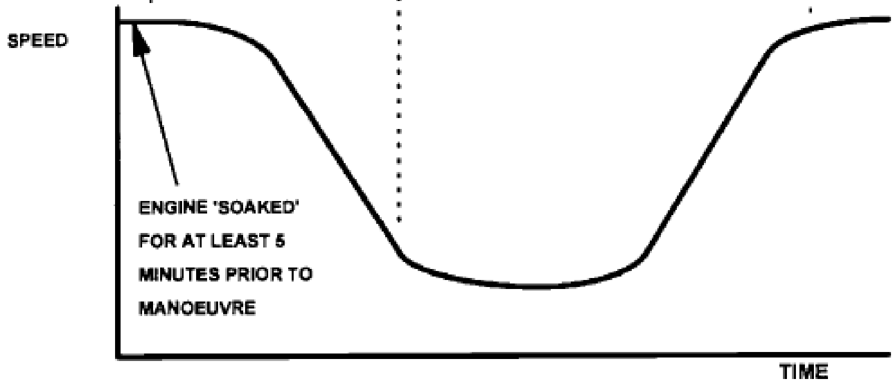
- Whenever longer engine response times than those for slam manoeuvres are acceptable to the application, PLA and hence fuel flow are changed at a slow rate.
- This greatly eases the operability concerns described later, as well as increasing engine cyclic life.

The hot reslam or Bodie:

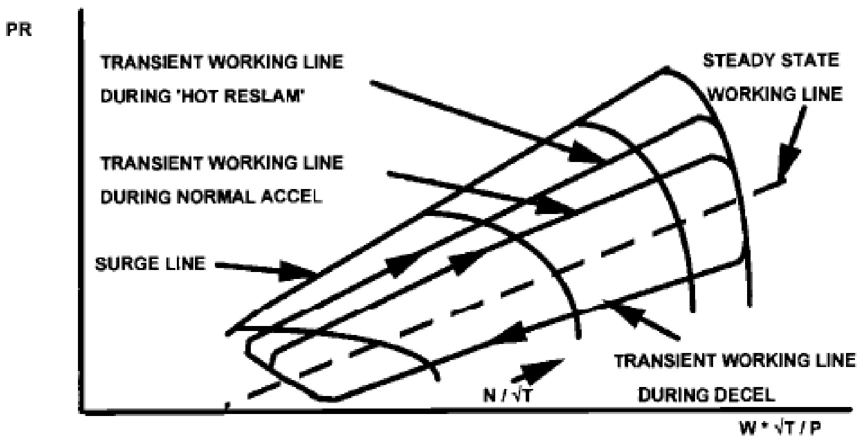
- The hot reslam is a particularly severe maneuver described in Fig. 8.4 and is only used in service during an emergency.
- It is also referred to as a Bodie, being named after a US air force pilot who first used the maneuver during engine flight trials.
- First the engine is held at a high power condition for at least 5 minutes to ensure the carcass has soaked to its hot condition.
- A slam decel to around idle is followed immediately by a reslam back to high power, allowing no time for the carcass to thermally soak at the low speed.



(a) Power lever angle versus time



(b) Engine speed versus time



(c) HP compressor transient working line

Fig. 8.4 The hot reslam or 'Bodie' manoeuvre.

- In the combustor and turbines heat soakage is akin to additional fuel flow, and in the HP compressor it lowers the surge line.
- The adverse impact on the transient HP compressor working line is also shown in Fig. 8.4.
- This manoeuvre is used during engine development programmes to give the engine harder operation than it will normally see in service to search for any potential surge margin deficiencies.

3.7 Case Study for a Single Shaft Jet Engine

Turboshaft / Turboprop, single spool

Here a turbine drives both the engine compressor and the output load. When power is extracted from a shaft two referred parameter groups, rather than just one, must be fixed in order to fix all others. Referred power is used as a base parameter for the charts for this configuration alone, because it is almost solely employed for power generation where the shaft must rotate at synchronous speed irrespective of power level.

Referred compressor delivery pressure and temperature increase significantly as day temperature is reduced and referred speed increases. For a given day temperature, at part power referred turbine temperatures fall sharply as fuel flow is reduced. Referred compressor delivery pressure and temperature fall only very slowly, due to the fixed speed. SFC becomes worse as the cycle efficiency reduces at the low firing temperature, and also as compressor efficiency falls.

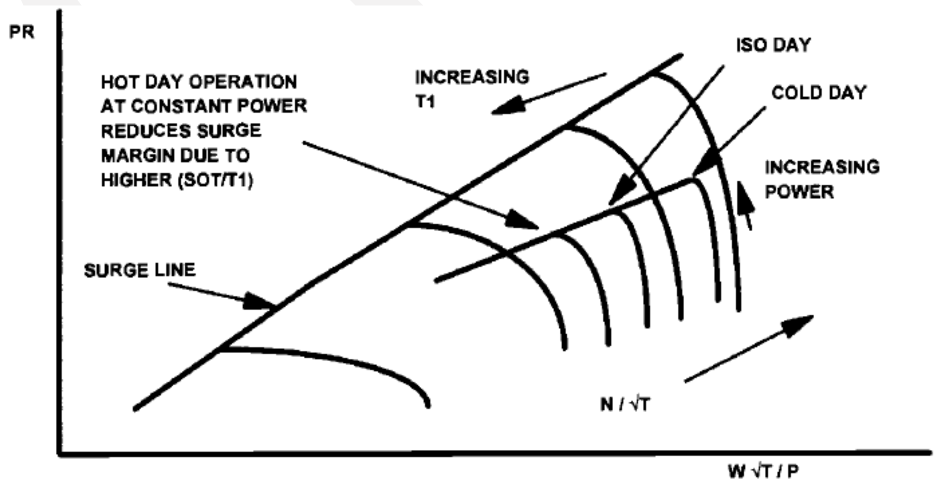


Fig. 7.1 Compressor working line, single spool turboshaft or turboprop.

Figure 7.1 shows that for a given day temperature as fuel flow, hence SOT and output power, are increased the compressor operating point moves up the constant referred speed line. Equally if day temperature increases referred speed falls. If the engine is flat rated to hold constant power then on hot days surge margin will reduce, as referred SOT must increase.

Turbojet, single spool

Here a compressor is driven by a turbine, which exhausts into a propelling nozzle. The pressure ratio across this nozzle results in high exhaust gas velocities, and hence jet thrust.

Subsonic operation:

Fig. 7.6 the compressor working line. An additional parameter relative to the land based engines is flight Mach number. The engine has a unique referred running line for each level of flight Mach number. Only once the propelling nozzle chokes do these running lines become coincident. The thrust level at which choking occurs depends on flight Mach number, which produces different levels of nozzle pressure ratio. Referred fuel flow, air flow and turbine temperatures show a strong variation versus Mach number at lower referred speeds, via variation of turbine expansion ratio into the unchoked propelling nozzle.

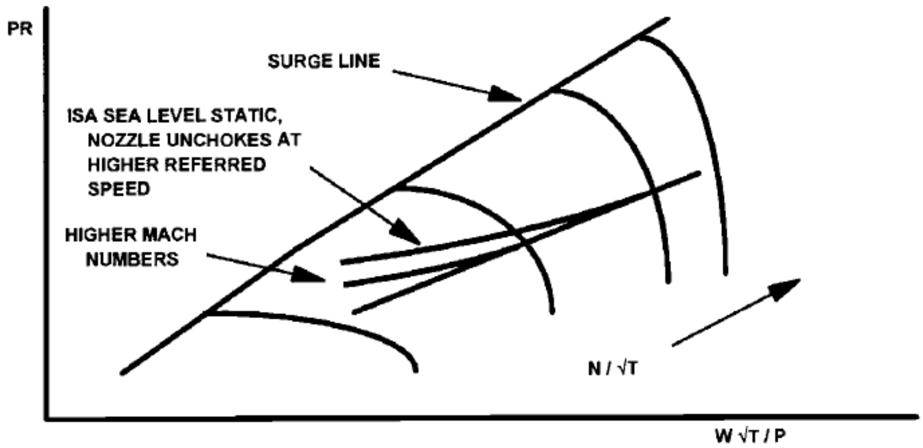


Fig. 7.6 Compressor working lines, subsonic turbojet, single spool.

As Mach number increases at a referred speed level referred mass flow increases, referred fuel flow reduces and the referred turbine temperatures are therefore lower. The exact variation of referred P3 depends on the compressor map shape, the small amount shown corresponds to relatively flat speed lines.

Unlike the land based engines, SFC improves significantly down to around 50% thrust due to increasing propulsive efficiency outweighing falling thermal efficiency of the core engine cycle. This is due to lower exhaust velocities and temperatures, and hence less energy used for any level of exhaust momentum (i.e. thrust). At lower thrust levels SFC worsens again, due to rapidly deteriorating thermal efficiency.

The largest effect of flight Mach number is via inlet momentum drag, which reduces net thrust and therefore worsens SFC. The ‘ram’ compression partly offsets this, and the available physical (rather than referred) thrust is high at cruise altitude. For early civil airliners with turbojets rather than turbofans, achieving takeoff thrust rather than cruise sized the engines.

3.8 Starting Process (Thrust engine start envelope/Starting torque and speed requirements)

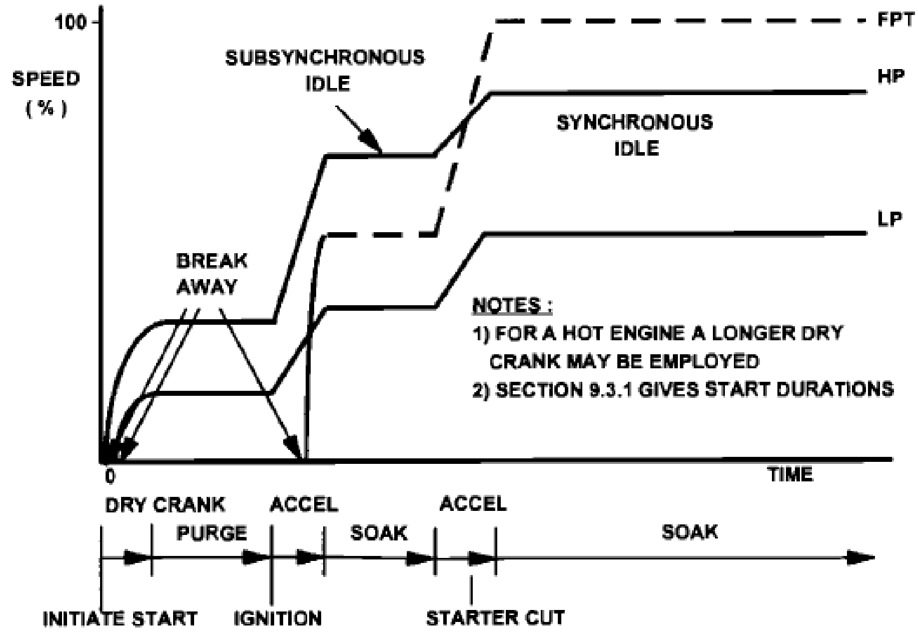
Start phases

The key phases of a start are briefly defined below. Each is then comprehensively described in the ensuing sections.

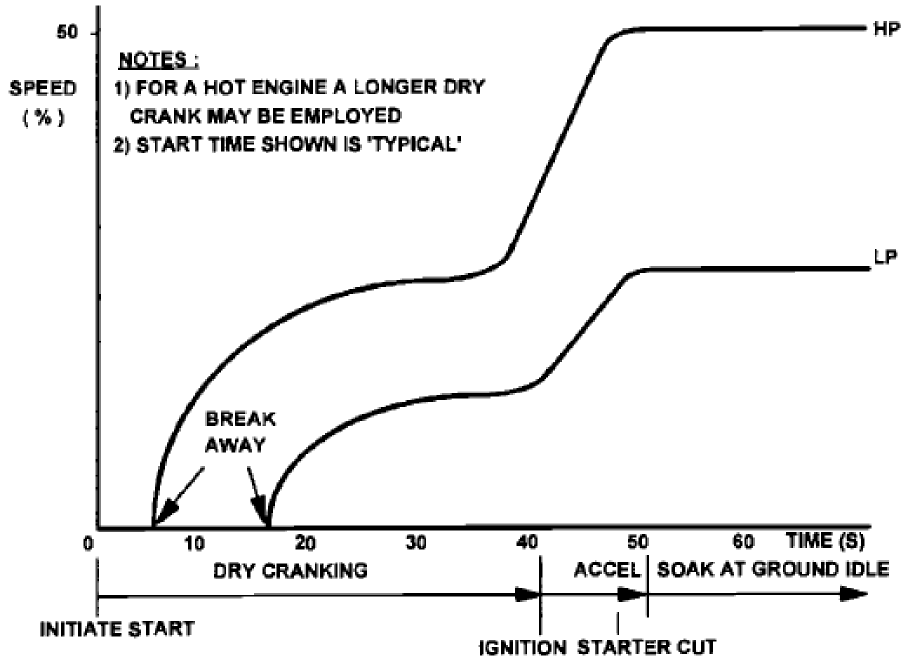
Dry cranking:

- The engine HP shaft is rotated by the starter with no fuel being metered to the combustor.
- The purpose of dry cranking is to develop sufficient pressure and mass flow in the combustor to permit light off. At start initiation the starter is energized and applies torque to the HP spool.
- To minimize shock torque loads torque may be applied gradually, for example via slow opening of air valves for a turbine starter.
- The HP spool then rotates and accelerates due to the excess starter assistance power.
- The airflow induced by the HP compressor causes the LP spool and if applicable eventually the free power turbine to break away from the oil at the bearings.
- As is apparent from Fig. 9.2, starter torque peaks shortly after start initiation, while starter power typically peaks at about 50% of the idle speed.
- In the dry crank phase the engine provides a resistance on the HP spool which increases with cranking speed, the turbine output power being less than that taken by the compressor, auxiliaries, bearings and disc windage.

- At all times the LP compressor power input is provided entirely by the LP turbine. It is usual to have handling bleed valves open during starting to lower working lines and, for inter stage bleeds, to raise the surge line.



(a) Two spool gas generator plus free power turbine powergen engine



(b) Two spool turbojet or turbofan

Fig. 9.1 Key engine start phases and speeds versus time.

- The achievement of adequate driving pressure ratio for the bleed valves to pass flow is crucial, levels should be assessed early in the design phase.
- At low LP spool speeds LP compressor delivery bleed valves actually suck air in.

- Invariably the starter cranks the HP spool rather than the LP, this being the most efficient way to provide the combustor mass flow and pressure to enable ignition and light around.
- Starting is eased for engines which have a high fraction of their pressure ratio developed by the HP compressor, as accelerating these stages via direct input shaft power avoids energy loss to the low efficiency of the LP turbine at these conditions.
- A related effect is that a relatively high LP spool inertia lengthens the time for that spool to accelerate, and hence the whole start sequence.
- The alternative of cranking an LP spool would incur worse pressure losses upstream of the combustor in the HP compressor.

Purging:

- This ensures that there is no fuel from previous operation or failed start attempts in the engine gas path or exhaust that may ignite and cause damage.
- The engine is dead cranked at the maximum speed the starter can sustain, which purges any fuel into the atmosphere.
- Purging is required for all starts and restarts with gas fuel, and may be used for liquid fuels following a failed start or emergency shut down.
- Where required purging typically lasts for 1–10 minutes depending on engine size and the type of unburnt fuel to remove.
- The dead crank phase where purging is performed does not appear on Fig. 9.2. There the combustor has been lit before the HP spool has accelerated to a point where the engine net resistance equals the starter assistance.

Light off - ignition and light around:

- Fuel is metered to the combustor, and ignitors are energized. This causes ignition locally within the combustor, and then light around of all the burners.
- Here the ignitors are activated and a constant light off flat of fuel flow is metered to the combustor by the control system.
- The light off flat may be as low as 300kW for a small RPV turbojet and up to 5000 kW for a large turbofan.
- Once fuel has ignited local to the ignitor, the flame must propagate and stabilize circumferentially around the combustor.

- The HP speed at which the combustor conditions are suitable for light off must be found from a combination of modelling, combustor rig testing and finally engine testing.

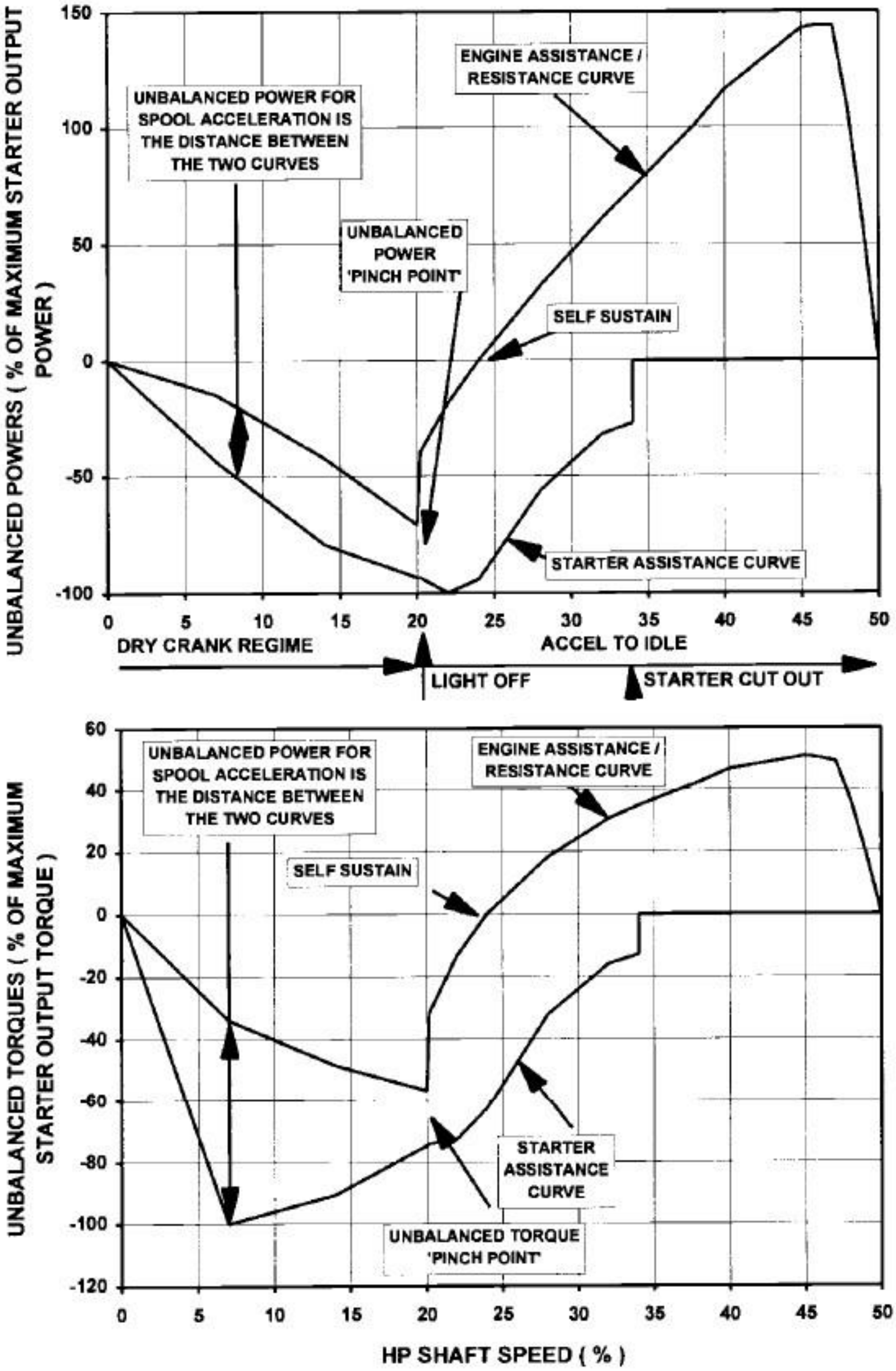
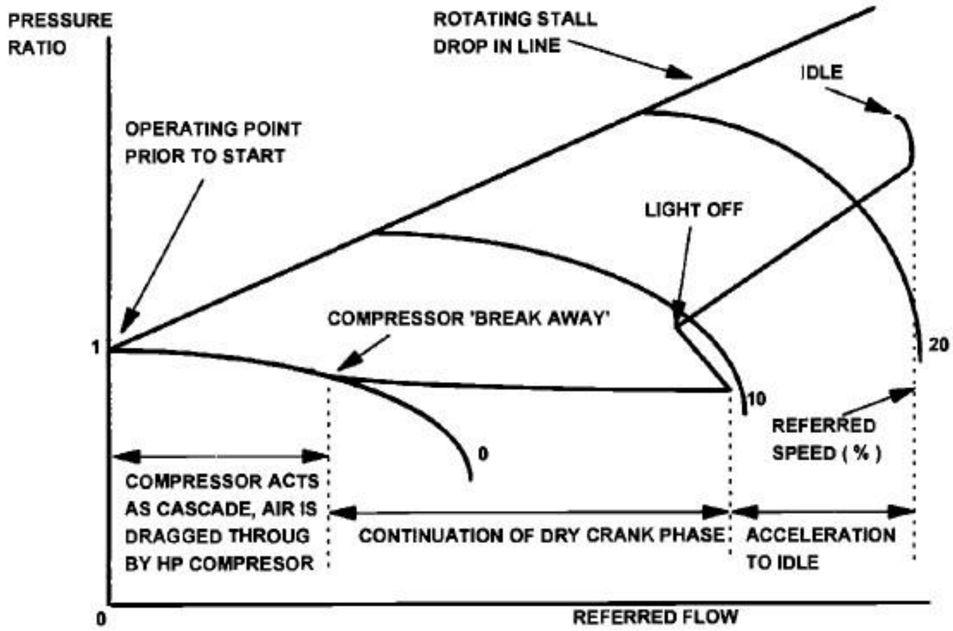


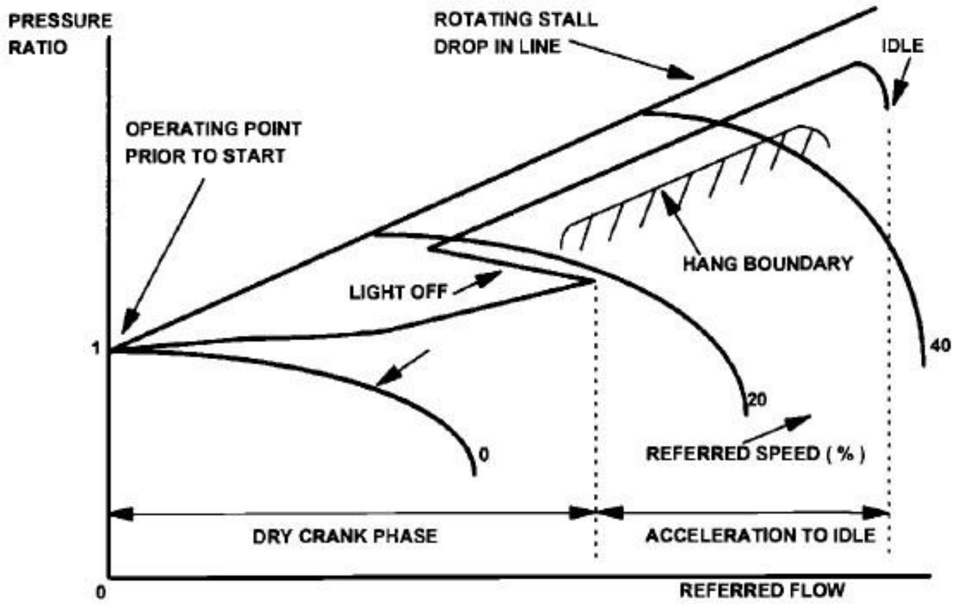
Fig. 9.2 Torque and power on the HP spool during starting.

- Light off is a key combustor condition with many practical issues to be overcome such as the atomization of kerosene or highly viscous diesel on cold days.

- Combustor efficiency is typically 10–50% at light off, which usually occurs between 15% and 25% HP speed. The lower values are generally for high altitude relight.
- Combustion efficiency versus loading and may be used to first-order accuracy in the start regime.



(a) Fan, LP or IP compressor



(b) HP compressor

Fig. 9.3 Compressor transient working lines during starting.

- Figure 9.2 shows that on light off there is a step reduction in engine resistance, however starter assistance is still required to continue HP spool acceleration.

- Turbine power output is still usually less than the sum of compressor input power, bearing and windage losses, and auxiliary requirements.
- Figure 9.3 shows that both compressor working lines also show a step upwards due to light off, with the HP compressor being the closest to the rotating stall drop in line.
- It is essential that the starter motor size, hence HP speed at the top of crank, and the light off flat are chosen such that the HP compressor does not go into rotating stall.
- The control system usually detects ignition and light around by means of thermocouples placed rearwards in the turbines.
- If light off does not occur within some specified time (e.g. 10 seconds) the control system aborts the start, shuts off fuel flow and commences a purging phase.

Acceleration to idle:

- This is achieved via a steady increase in fuel flow, and continuing starter assistance.
- Fuel flow is steadily increased, causing the engine to accelerate towards idle very much as per the above idle accels.
- The starter motor continues to provide crank assistance well after light around. As speed increases the engine assistance eventually dwarfs that of the starter, which cuts out before idle via de-energization and declutching.
- As shown on Fig. 9.2, the engine resistance crosses the 'X' axis and becomes assistance shortly after light off. This point is called self-sustain and theoretically if the starter motor were cut the engine could operate there steady state.
- However combustor exit temperature profiles make this impractical with respect to turbine life, and hence this speed must be passed through transiently.
- During acceleration fuel flow is scheduled such that the compressor working lines run approximately parallel to the rotating stall drop in line.
- Many combustion systems employ separate, lower flow injectors for starting. This is because at low fuel flows the main injectors may not produce adequate atomization; here the combustor stability and efficiency depend strongly on which injectors are in use.
- In many cases below a certain threshold the main burner system may in fact pass no flow at all. The point of changeover between systems must be chosen with these issues in mind, to avoid extinction, stall or hang.

- On reaching idle, fuel flow is cut back and the engine assistance/resistance becomes zero; no unbalanced power is required for steady state idle operation.
- The idle point on the HP compressor map is below the transient start working line, whereas for the LP compressor it is higher.
- Heat soakage, can have a very significant impact on working lines for hot restarts or cold soaked starts. For an immediate restart following shut down heat transfer from the carcass is akin to additional fuel flow, and will push the compressor towards rotating stall and increase turbine temperatures.
- In addition, the compressor surge lines are lowered,. Conversely, after a prolonged cold soak, heat transfer to the carcass is akin to reduced fuel flow and may drive the engine towards hang.

Thermal soakage:

- Engines are often held at idle to allow the carcass to thermally soak to the new temperature to preserve cyclic life.

3.9 Windmilling

Windmilling occurs when air flowing through an unlit engine causes spool rotation. This phenomenon applies mostly to aircraft engines, where it is caused by ram pressure.

Examples include when an engine has flamed out during flight, or an unmanned air launched vehicle is being carried by a parent aircraft prior to launch. The direction of rotation is the same as for normal operation. Under certain conditions windmilling also occurs for land based and marine engines.

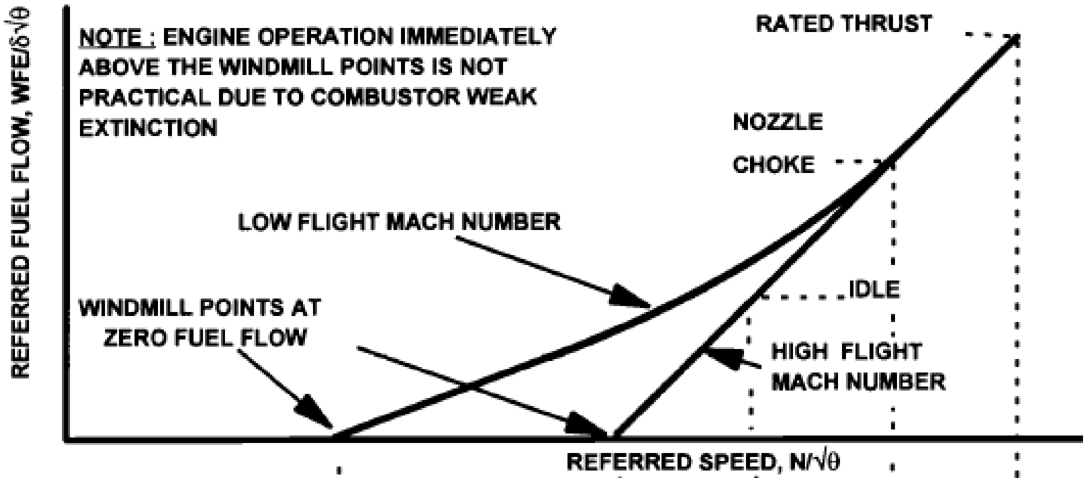
Free windmilling is where all the engine spools are free to rotate. Locked rotor windmilling is where the HP spool is mechanically prevented from rotating.

A knowledge of key performance parameters during windmilling is essential:

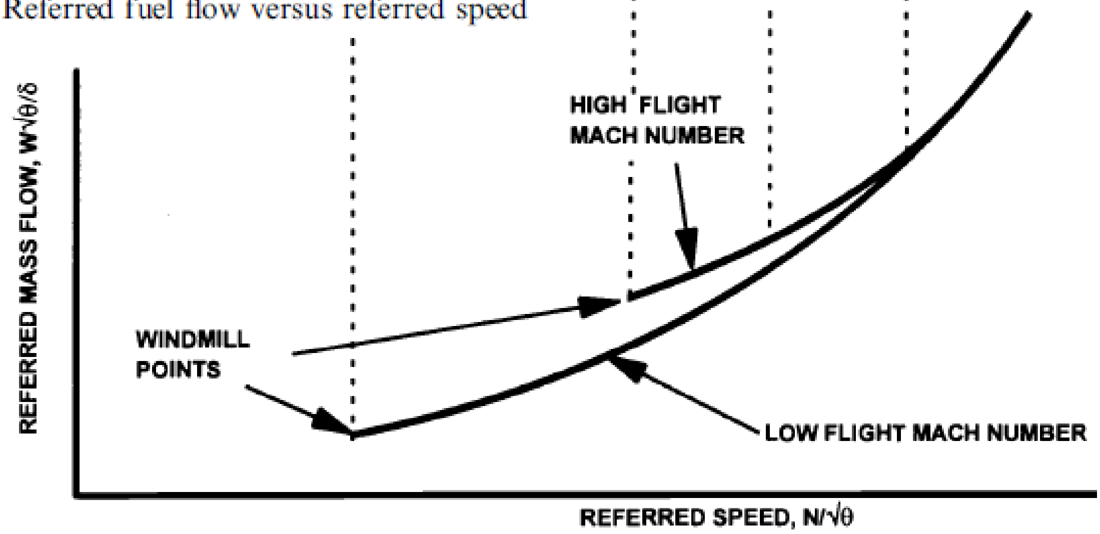
- To ensure successful light or relight, appropriate combustor design requires knowledge of combustor entry pressure, temperature and mass flow.
- The aircraft systems designers must know how much power may be extracted from the engine, if any.
- To understand bearing lubrication requirements, and how engine auxiliaries will perform, rotational speeds are required.

- The aircraft designers must know the engine drag (i.e. negative thrust) during windmilling. Drag is caused by air slowing down as it passes through the engine.

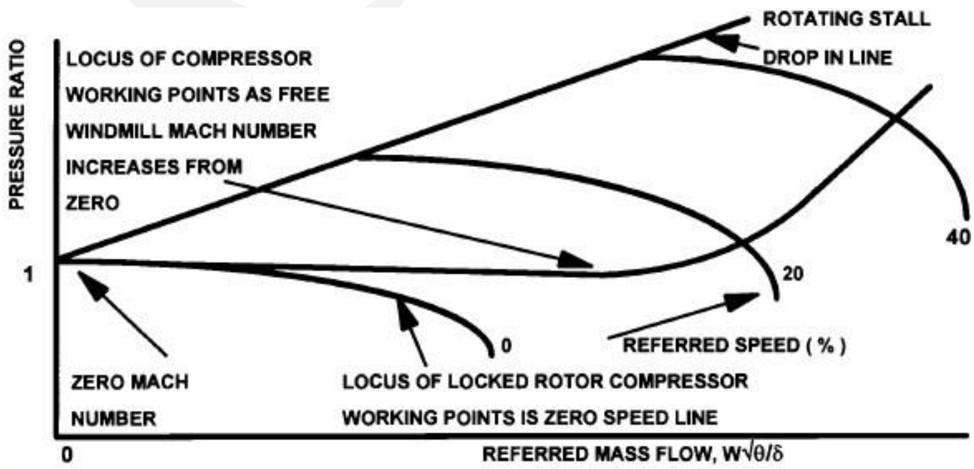
The Turbojet Windmilling Process:



(a) Referred fuel flow versus referred speed



(b) Referred mass flow versus referred speed



(c) Compressor working points

Fig. 10.1 Turbojet windmilling: referred parameter group relationships.

Figure 10.1 shows schematically how the usual non-dimensional relationships can be extended to the windmill regime. Referred fuel flow and mass flow are shown versus referred speed for a high and low flight Mach number; a locus of windmill points is apparent at the windmill condition of zero fuel flow. Mass flow increases with flight Mach number, as the higher the Mach number the higher the referred speed. Operation on the lower parts of the curves may not be practical since the combustor is likely to weak extinct in this regime, causing the engine to decelerate to the windmill point. Other referred parameter groups may be plotted in this manner. Finally, Fig. 10.1 shows the locus of operating points for free and locked rotor windmilling on the low speed compressor map.

The pressure and temperature ratios at key stations through a turbojet while windmilling. The compressor behavior depends on flight Mach number:

- As flight Mach number is increased from zero, compressor pressure ratio initially falls from the value of one. The temperature ratio is greater than one however, and hence the compressor is operating as a stirrer or paddle. For a multi-stage axial flow compressor some front stages may actually perform as a turbine but overall the machine has a net work input.
- As Mach number increases further, pressure ratio increases and eventually exceeds one. This is particularly true for high design pressure ratios and multiple axial stages. Here the compressor overall, and certainly the back stages, function in the true compressor fashion. Typically the higher the design pressure ratio, the higher the windmill pressure ratio at a given flight Mach number. For a given design pressure ratio centrifugal compressors tend to have a lower pressure ratio at a flight Mach number, due to the absence of back stages able to operate normally.

During steady state windmilling the compressor always absorbs power overall. Otherwise the shaft would accelerate as there is no other significant power absorption mechanism, bearing and windage losses being small. The turbine is able to supply the compressor input power because there is an expansion ratio remaining after all pressure drops due to ducts, combustor and possibly compressor(s) have been deducted from the ram pressure ratio. The combustor, intake, exhaust and other ducts impose pressure losses with no change to total temperature.

The expansion ratio across the propelling nozzle is small and is typically independent of turbojet design pressure ratio. Total temperature at the nozzle is slightly lower than the ram temperature. This small drop is due to any work extracted by the bearings and engine auxiliaries, the effects of compressor and turbine work otherwise cancelling each other.

The Turbofan Windmilling Process:

The bypass duct presents the path of least resistance to the ram pressure at the fan face, hence most flow takes this path. This means that the fan demands high work input and therefore the core must match such that a high expansion ratio is available for the LP turbine. The HP turbine therefore has a low power output, and the HP compressor has a significantly lower pressure ratio than in an equivalent turbojet.

The Windmilling Process for a Single Spool Turboprop:

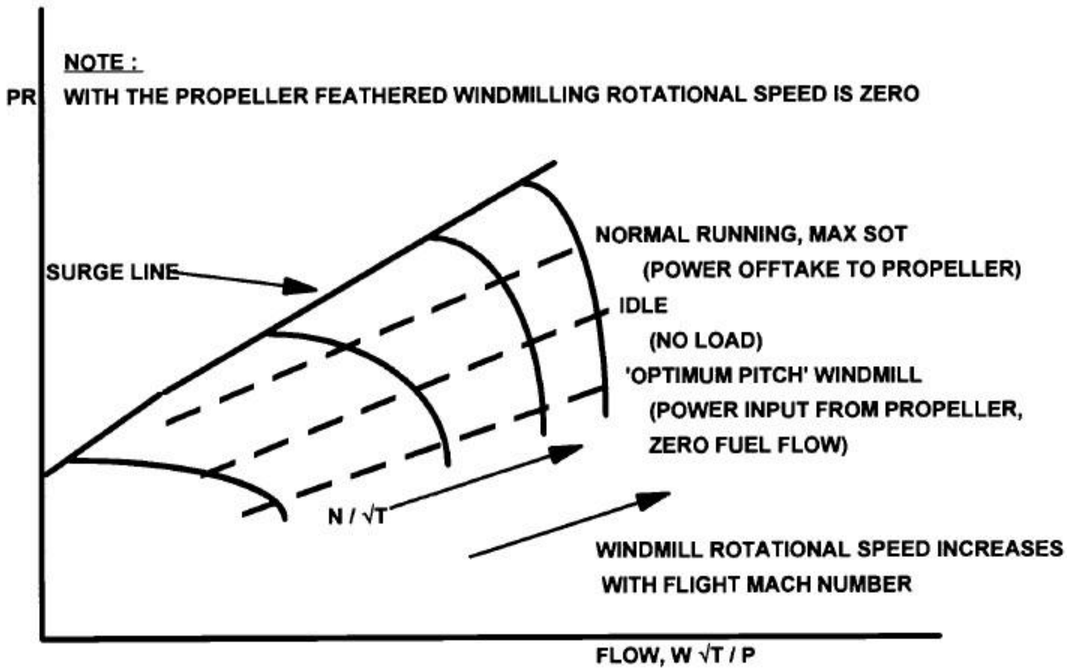


Fig. 10.2 Single spool turboprop windmilling: compressor working lines.

Windmill tests in an altitude facility on two single spool turboprops, with the propeller pitch set for maximum windmill rotational speed. In this configuration the propeller acts as a turbine, dropping pressure and temperature, and hence producing shaft power. The result is that 100% referred rotational speed is achieved at a flight Mach number of less than 0.4, and substantial customer power extraction is available. The compressor pressure ratio is greater than one for all flight Mach numbers as it is driven by both the propeller and turbine. As shown by Fig. 10.2, the compressor working line is lower than the no load line during normal operation, due to zero fuel flow and hence zero combustor temperature rise. For the 100% referred speed case pressure ratio is approximately 25% of its ISO takeoff design point value. This pressure ratio, less combustor and duct pressure losses, is available for expansion across the turbine. Referred air mass flow is approximately twice that of a turbojet at the same flight Mach number.

The drag is predominantly created by the propeller. At high flight speeds the magnitude of the drag would approach that of cruise thrust in normal operation. In actual flight situations such a large drag makes it impractical to operate with the propeller pitch as above. Hence engines are fitted with a 'reverse torque switch' in the gearbox, which senses windmill operation by the change in direction of torque due to the propeller driving the engine (as opposed to vice versa). The control system then coarsens the pitch to the feathered position where the propeller blades are parallel to the direction of flight, preventing any engine rotation and ensuring drag is minimal.

The Windmilling Process for a Free Power Turbine Turboprop:

In this instance the propeller must be feathered immediately since it will otherwise overspeed the power turbine. There is no connection to the compressor to absorb the output power from the propeller and the power turbine itself. Only a small fraction of the available power is absorbed by auxiliaries, bearings and windage.

3.10 Engine Performance Monitoring

In recent years, a method of monitoring the gas turbine engine's day-to-day condition has been adopted by many operators. In this system the EPR (engine pressure ratio), rpm, F/F (fuel flow), EGT (exhaust gas temperature), and throttle position are used to determine the aerodynamic performance of the engine, while vibration amplitude and oil consumption (which may include periodic spectrometric oil analysis) is used to evaluate mechanical performance.

Although specific procedures will vary from operator to operator, in general, cockpit instrument readings are taken once a day or on every flight during cruise conditions. The recorded data is then processed in a variety of ways and compared with "normal" data established by the manufacturer or the operator as representing the normal performance of the engine, Trends in the operating parameters are then observable. The data may also be collected automatically during the flight and then off-loaded for analysis by ground personnel.

Engine performance monitoring is proving to be a very effective method of providing early warning information of ongoing or impending failures, thus reducing unscheduled delays and more serious engine failures. Examples of several actual engine malfunctions that were detected using performance monitoring techniques.

3.11 Formulae

PERFORMANCE TESTING

As indicated previously in this book, the performance of any engine is considerably influenced by changes in ambient temperature and pressure because of the way these parameters affect the weight of the air entering the engine. In order to compare the performance of similar engines on different days, under different atmospheric conditions, it is necessary to "correct" a given engine's performance to the standard day conditions of 29.92 inHg [101.3 kPa] and 59°F (519°R) [15°C (288°K)].

For example, the following conditions are known about a running engine:

1. rpm = 9465
2. EGT = 510°C (950°F or 1410°R). See note that follows.
3. W_f = 4000 lb/h [1814.4 kg/h]
4. W_a = 200 lb/s [90.7 kg/s]. (Although airflow is listed here, it is difficult, if not impossible, to measure the weight of airflow directly. Airflow can be determined indirectly through pressure measurements in the engine.)
5. F_n = 10,000 lb [4536 kg]
6. TSFC = 0.400

Barometric pressure	= 30.3 inHg [102.6 kPa]
Standard day pressure	= 29.92 inHg [101.3 kPa]
Ambient temperature	= 82°F [27.8°C]
Standard day temperature	= 59°F + 460° (519°R) [15°C + 273°C (288°K)]

[**Author's Note** To convert degrees Fahrenheit to degrees Rankine, add 460 to the Fahrenheit reading. To convert degrees Celsius to degrees kelvin, add 273 to the Celsius reading.]

Since these are all "observed" measurements, they must be *corrected* in order that valid comparisons can be made between engines. To change the observed operating parameters to the corrected values, i.e., the rpm, EGT, F/F, A/F, F_n, and TSFC that the engine would have if it were running under standard day conditions, it is necessary to apply a pressure correction factor, delta (δ), and a temperature correction factor, theta (θ).

$$\delta = \frac{\text{observed pressure (inHg)}}{\text{standard day pressure (inHg)}}$$

$$\theta = \frac{\text{observed temp. (°R)}}{\text{standard day temp. (°R)}}$$

For the atmospheric conditions stated above, delta and theta will be

$$\delta = \frac{30.3}{29.92} = 1.013$$

$$\theta = \frac{82 + 460}{59 + 460} = \frac{542}{519} = 1.045$$

$$\sqrt{\theta} = 1.022$$

[**Author's Note** See pages 178–179 for the reason the square root of theta is needed. See appendix D for tables listing the values of delta and theta for various pressures and temperatures.]

To correct the observed data gathered for the above engine, the following formulas are used.

1. Corrected rpm = $\dfrac{\text{observed rpm}}{\sqrt{\text{temperature correction factor}}}$

or

$$rpm_{corr} = \frac{rpm_{obs}}{\sqrt{\theta}}$$

2. corrected EGT = $\dfrac{\text{observed EGT (°R)}}{\text{temperature correction factor}}$

or

$$EGT_{corr} = \frac{EGT_{obs}}{\theta}$$

3. Corrected fuel flow =

$$\frac{\text{observed fuel flow}}{\text{pressure correction factor} \times \sqrt{\text{temperature correction factor}}}$$

or

$$W_{f,corr} = \frac{W_{f,obs}}{\delta\sqrt{\theta}}$$

4. Corrected airflow =

$$\frac{\text{observed airflow} \times \sqrt{\text{temperature correction factor}}}{\text{pressure correction factor}}$$

or

$$W_{a,corr} = \frac{W_{a,obs}\sqrt{\theta}}{\delta}$$

5. Corrected thrust = $\dfrac{\text{observed thrust}}{\text{pressure correction factor}}$

or

$$F_{n,corr} = \frac{F_{n,obs}}{\delta}$$

6. Corrected TSFC =

$$\frac{\text{observed fuel flow}}{\text{observed thrust} \times \sqrt{\text{temperature correction factor}}}$$

or

$$TSFC_{corr} = \frac{W_{f,obs}}{F_{n,obs}\sqrt{\theta}} = \frac{TSFC_{obs}}{\sqrt{\theta}}$$

Additional corrections for humidity and variable-specific-heat fuels are also made on some engines.

Using the observed operating parameters given above, we find the corrected values to be

1. $rpm_{corr} = \dfrac{rpm_{obs}}{\sqrt{\theta}} = \dfrac{9465}{1.022} = 9261$ rpm
2. $EGT_{corr} = \dfrac{EGT_{obs}}{\theta} = \dfrac{1410}{1.045} = 1349°R = 889°F$ $= 476°C$
3. $W_{f,corr} = \dfrac{W_{f,obs}}{\delta\sqrt{\theta}} = \dfrac{4000}{1.013 \times 1.022} = 3864$ lb/h [1752.7 kg/h]
4. $W_{a,corr} = \dfrac{W_{a,obs}\sqrt{\theta}}{\delta} = \dfrac{200 \times 1.022}{1.013} = 202$ lb/s [91.6 kg/s]
5. $F_{n,corr} = \dfrac{F_{n,obs}}{\delta} = \dfrac{10{,}000}{1.013} = 9872$ lb [4477.9 kg]
6. $TSFC_{corr} = \dfrac{W_{f,obs}}{F_{n,obs}\sqrt{\theta}} = \dfrac{4000}{10{,}000 \times 1.022} = 0.391$

If one knows the corrected values (given in the manufacturer's performance specifications), engine operating parameters for *any* pressure and temperature can be computed as follows:

1. $rpm_{obs} = rpm_{corr}\sqrt{\theta}$
2. $EGT_{obs} = EGT_{corr}\,\theta$
3. $W_{f,obs} = W_{f,corr}\,\delta\sqrt{\theta}$
4. $W_{a,obs} = \dfrac{W_{a,corr}\,\delta}{\sqrt{\theta}}$
5. $F_{n,obs} = F_{n,corr}\,\delta$
6. $TSFC_{obs} = TSFC_{corr}\,F_{n,obs}\sqrt{\theta}$

Previous exam questions:

1. (10AE74 - Dec. 2017/Jan. 2018)

a. Explain the transient performance phenomena of engine. (10M)

b. How the performance of single spool turbo prop engine is evaluated? Explain transient working lines during declaration, with suitable graph. (10M)

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

a. What are the design point performance parameters that are involved in gas turbine engine? (10M)

b. Write the steps involved in starting of jet engine. (3M)

c. Draw and explain a typical restart envelope for a civil turbofan engine. (7M)

d. A turbo jet engine performance data is given below: (10M)

RPM = 9500; EGT = 450^0 C; W_f (fuel consumption) = 1800 kg/hr; W_a (air consumption) = 91 kg/sec; TSFC = 0.5. The test is carried out at a pressure of 102.6 KPa and ambient temperature of 30^0 C. Correct the test data for ISA conditions (Pressure 101.3 KPa and temperature 15^0 C). Take F_n (Net thrust) = 4510 kg.

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

a. What do you mean by design and off design and transient performance? What are the different parameters in design point performance? (10M)

b. Mention the steps involved in starting of gas turbine engine. (10M)

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

a. What is Windmilling? Explain the turbojet windmilling process. (12M)

b. Explain the concept of inflight restart envelope of a turbo fan engine. (8M)

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

a. What do you mean by design and off design and transient performance? What are the different parameters in design point performance? (8M)

b. Mention the steps involved in starting of gas turbine engine. (4M)

c. Explain the concept of inflight restart envelope of a turbofan engine. (8M)

6. (6AE74 – December 2012)

a. What is windmilling? Explain the turbojet windmilling process. (10M)

b. The observed measurements of a running engine are: (10M)

RPM = 9465; EGT = 510^0 C; Wf (fuel consumption) = 1814.4 kg/hr; Wa (air consumption) = 90.7 kg/sec; TSFC = 0.4; Fn (Net thrust) = 4510 kg; Barometer pressure = 102.6 kPa; ambient temperature = 27.8^0 C. Correct the test data for ISA conditions (Pressure 101.3 KPa and temperature 15^0 C).

7. (6AE74 – December 2011)

a. Explain the performance characteristics of gas turbine. (8M)

b. How performance of a single spool turbojet is evaluated? (12M)

8. (6AE74 – Jun/July 2011)

a. Explain transient performance of an engine. (12M)

b. Calculate surge margin for the following data: (8M)

New production engine to engine working line variation	= 0 ± 1.5%
Engine to engine surge line variation for production engines	= 0 ± 4.0%
In service working line deterioration	= - 2.0%
In service surge line deterioration	= - 4.0%
Control system fuel metering VIGV position etc.	= 0 ± 1.0%
Reynolds number effect	= - 1.0%
Intake distortion	= - 1.0%
Transient allowance	= -12.0%

9. (6AE74 – December 2010)

a. Explain the fundamental starting process of a jet engine. (10M)

b. A jet engine performance data is given below: (10M)

RPM = 9500; EGT = 450^0 C; Wf (fuel consumption) = 1830 kg/hr; Wa (air consumption) = 91 kg/sec; TSFC = 0.5; Fn (Net thrust) = 4510 kg; The test is carried out at a pressure of 102.6 KPa and ambient temperature of 30^0 C. Correct the test data for ISA conditions (Pressure 101.3 KPa and temperature 15^0 C).

10. (6AE74 – Dec.09/Jan.10)

a. The observed measurements of a running engine in a case study are: (20M)

RPM = 9465; EGT = 510^0 C; Wf (fuel consumption) = 1814.4 kg/hr; Wa (air consumption) = 90.7 kg/sec; TSFC = 0.4; Fn (Net thrust) = 4536 kg; Barometer pressure = 102.6 kPa; ambient temperature = 27^0 C. Correct the engines performance to the standard day conditions of 101.3 KPa and 15^0.

GTT