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GAS TURBINE ENGINES (CASA ATPL)

CHAPTER 8 – PERFORMANCE

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THRUST MEASUREMENT

The thrust rating of an engine is calculated by subtracting the rearward acting gas load forces from the forward acting gas load forces. This provides the Gross Thrust of an engine. This is usually done on an engine test rig. Refer to Figure 8-1.

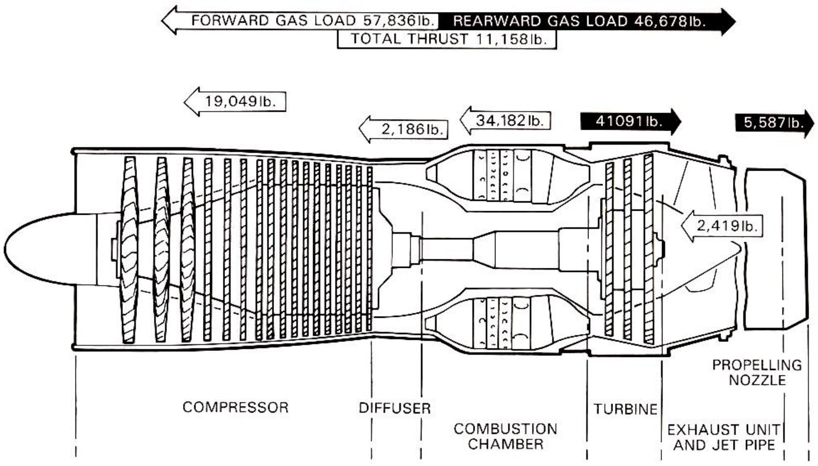

Figure 8-1 Thrust Calculation

Power Output Indicators.

It is important for the pilot to appreciate the relationship between thrust and RPM, fuel flow and turbine temperature. It is reasonable to assume that for any significant increase in fuel flow the turbine temperature should increase, causing an increase in engine RPM and hopefully an increase in thrust. It should be easy to see that if one of these variables changes, then there should be a corresponding change in the other three.

For instance, the results of turning on the Engine Inlet Anti-Ice or any air consuming system, would be a loss of thrust (EPR). As we are not altering the air flow at the compressor inlet, there will be no compensation by the fuel control to change the fuel air ratio, so fuel flow will remain constant. However, turbine temperature will increase as there is less cooling airflow. To return thrust to its original setting, power must be increased. This will result in an increase in fuel flow and a further increase in turbine temperature as well as an increase in Thrust Specific Fuel Consumption.

N1 VS EPR

Thrust measurement and indicating systems are displayed in a format that is determined by the engine manufacturers. Thrust can be indicated using either;

- Engine Pressure Ratio (EPR); or
- N_1, Fan or spool RPM.

EPR is Exhaust Gas pressure (P6) over Compressor Inlet pressure (P2) Refer to Figure 8-2, and is used on aircraft powered by Rolls Royce or Pratt & Whitney engines. EPR is a slightly more accurate measurement of thrust than N_1, but is more affected by changes in atmospheric conditions.

EPR however, can provide a misleading, higher reading if the P2 probe is blocked or iced up. This has led to several incidents in the past, including a B737 that crashed into the Potomac River in Washington DC in 1982, due to icing conditions.

N1 is used by aircraft powered by General Electric engines. N1 produces a more stable thrust indication, but becomes less accurate as engine performance deteriorates due to fan wear or damage. It should be noted that aircraft that use EPR will also display N1.

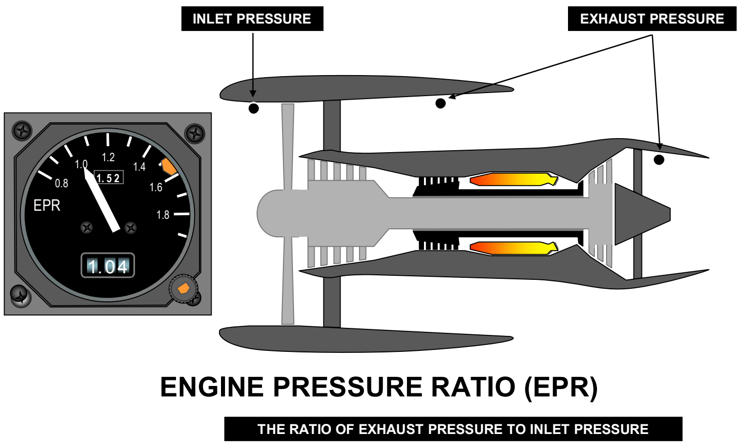

Figure 8-2 EPR Calculation

THRUST DEFINITIONS

Different engine manufacturers use differing terms and definitions regarding thrust. Listed below are some of the more common definitions, they are;

- ***Gross Thrust****,* or Static Thrust is the test bed measurement (aircraft not moving),
- ***Net Thrust*** is the static thrust adjusted for the aircraft velocity,
- ***Maximum Thrust****,* is the highest thrust available as determined by the FADEC, usually has a time limit (5 minutes or 10 minutes with one engine inoperative),
- ***TOGA*** is the thrust setting used for take-off and go-around as computed by the flight management system, using AUW, TAT, runway length and wind speed.

  For take-off, the advantage of having such a system is the ability to reduce wear and tear on the engines by only using as much power as is actually required to ensure the aircraft reaches a safe take-off speed.

  Activating TOGA on a go-around disables the autopilot so it does not follow the ILS glide slope, and it overrides any auto throttle mode which would keep the aircraft in landing configuration.

  The TO/GA switch can be used even after touchdown if reverse thrust has not been selected,
- ***Flex Thrust.*** An Airbus term for TOGA,
- ***Max Continuous Thrust***, the maximum thrust available with no time limit,

- ***Climb Thrust*** is the power setting for the best climb gradient, may be up to Max Continuous Thrust,
- ***Cruise Thrust*** is the most economical thrust setting, taking into account fuel economy and engine life,
- ***Flight Idle Thrust*** which is the minimum power setting for flight, again with the thrust levers at idle. The RPM is higher than Ground Idle to ensure a continued bleed air supply and to reduce spool up time, and
- ***Ground Idle Thrust*** is the ground thrust setting with the thrust levers on the idle stops, usually about 5% of take off thrust and just enough to taxi.

Flight Idle and Ground Idle is the same position for the thrust lever. Ground Air Sensing or Ground Air Logic is used to differentiate between the two. Some engines have a time delay for the RPM reduction to Ground Idle (four seconds), this reduces the spool up time for reverse.

THRUST SPECIFIC FUEL CONSUMPTION (TSFC)

As mentioned in Chapter 4, Thrust Specific Fuel Consumption (TSFC) is a measure of engine efficiency. It usually relates to compressor performance, propulsive efficiency and thermal efficiency. It is not the only consideration for the most economical cruise speed and altitude for the aircraft. It will be seen that the TSFC will remain essentially the same as the thrust decreases along with fuel burn as altitude increases. Refer to Figure 12-4.

Specific Fuel Consumption (SFC) is a term used to describe the efficiency of a turboprop.

FACTORS EFFECTING PERFORMANCE

It is essential for pilots to understand the effects of temperature, altitude and airspeed on the engine if they are to operate the aircraft efficiently, and prevent damage to the engine. The most significant factor affecting gas turbine performance is the Mass Airflow through the engine. Mass Airflow is the weight of the air passing through the engine per unit of time. adjusted for the effects of gravity.

EFFECT OF OUTSIDE AIR TEMPERATURE

On a cold day, the density of the air increases and the mass flow to the compressor is increased. This will result in an increase of thrust or shaft horsepower. However, the compressor will require more power to drive it, so requiring more fuel to be provided. If the fuel is not provided, the engine will run at a lower RPM.

On a hot day, the density of the air decreases resulting in a reduction of mass flow through the engine compressor, resulting in less power being produced. The compressor will require less power to drive it and the fuel control will reduce fuel to control RPM or turbine temperature, resulting in less power being produced. On a very hot day a 20% loss of thrust is not uncommon. To recover this, a thrust augmentation system may be used, such as a water or water/methanol injection system.

EFFECTS OF ALTITUDE

The effect of altitude on thrust is a function of density. Density is mass per unit volume. The amount of air entering the engine at a given RPM is controlled by the engine inlet; therefore the mass flow is determined by density.

A change in the free air temperature will affect the density of the air entering the engine. A decrease in temperature will result in an increase in density and an increase in temperature will result in a decrease in density.

A change in free air pressure will also affect density. An increase in air pressure will result in more molecules of air entering the engine inlet, which means a greater mass airflow. As pressure goes up, density goes up. As density goes up the weight of air goes up which results in an increase in thrust.

As an aircraft climbs, air pressure and temperature decrease. As pressure decreases, thrust decreases, but as temperature decreases thrust increases. Refer to Figure 8-4.

<u>Pressure drops off faster than temperature so there is a net drop off in thrust with an increase in altitude</u>. Refer to figure 8-3.

At approximately 36,000 feet, the temperature stops falling and remains constant, while the pressure continues to fall. <u>As a result the thrust drops off more rapidly above 36,000 feet</u>, which is considered the optimum altitude for long-range cruising, just before the rate of thrust fall-off increases.

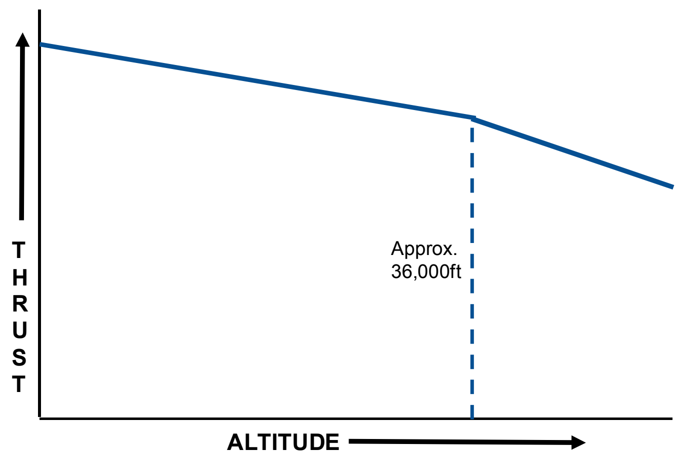

Figure 8-3 Thrust Lapse Rate

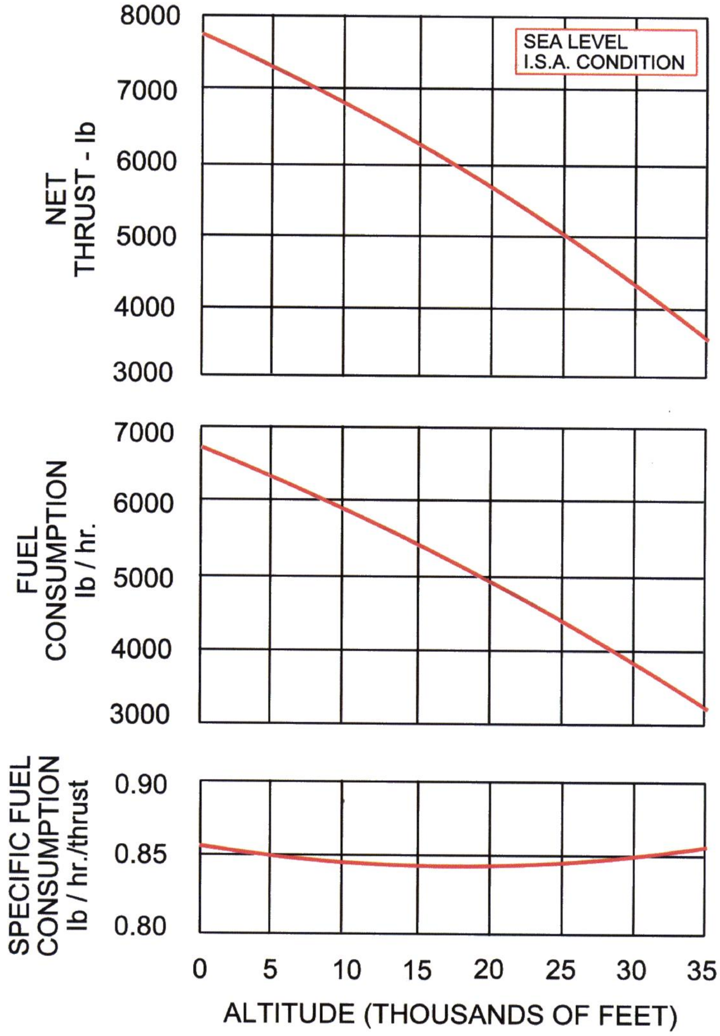

Figure 8-4 Effect of Altitude on Thrust

EFFECTS OF RPM

The input of heat energy needed to accomplish the required amount of work on a mass of air is controlled by the fuel system. The variation in mass airflow on which the work is done is controlled by the engine's RPM. To increase thrust, the fuel system must increase fuel flow, thereby increasing RPM. As RPM increases, it is easy to see that mass airflow through the engine increases, thrust increases and specific fuel consumption decreases. It should be pointed out though that the engine will be operating with an increased turbine temperature. At low engine speeds, the turbojet thrust increase is slight even for large increases in engine speed. At high engine speeds, even a small increase in RPM produces a large increase in thrust. Refer to Figure 8-5. (This can be likened to a low compression piston engine with low power output compared to a high compression engine representing a turbo jet at high RPM) The acceleration, or spool up time from a low idle speed to take-off RPM is a deficiency in turbine engines that through design and materials is gradually being overcome.

As has been mentioned throughout this text, there are many RPM settings used in the control of the gas turbine engine. Each of these settings has a special relationship to the operation of the aircraft and what the pilot is attempting to achieve. As design criteria the engine is required to operate most efficiently at 90 to 95% of its rated speed (that normally being referred to as 100%). When the engine is operated above or below this speed, thrust will increase or decrease but there will also be a corresponding increase in Specific Fuel Consumption

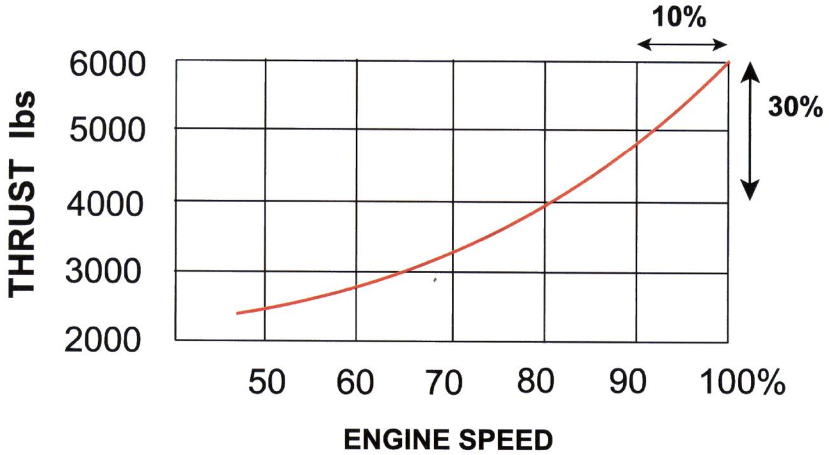

Figure 8-5 Effect of RPM on Thrust

EFFECTS OF AIRSPEED

As the aircraft begins to accelerate, the actual mass flow is reduced slightly due to the phenomenon known as <u>Intake Momentum Drag.</u> This causes a reduction in the thrust output from the engine. However, as the aircraft continues to accelerate, there is a thrust recovery caused by the increased airflow due to the effect of the air being "rammed" down the intake. This is known as <u>Ram Effect</u>. At around 300 knots the effects of Intake Momentum Drag are negated by Ram Effect and as airspeed increases, Ram Effect becomes more pronounced. <u>This explains improved turbojet performance as speed increases</u>. Refer to Figure 8-6.

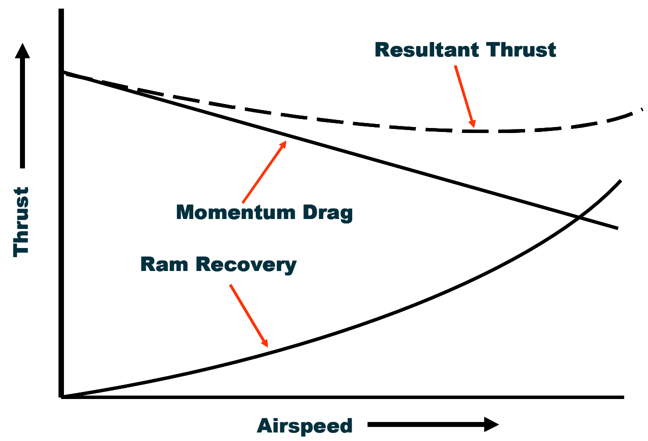

Figure 8-6 Effect of Airspeed on Thrust

EFFECTS OF HUMIDITY

As humidity increases, the density of the air entering the engine decreases due to the change in weight per unit volume. It is logical then that as humidity increases, the thrust output from the engine decreases, however the overall reduction is only slight and can be ignored for normal operations. All performance data ignores the effects of humidity.

ENGINE LIMITATIONS

Probably the most important operational limitation that pilots have control over is the turbine temperature, as the turbine is the area most significantly affected by abuse. The turbine's life is determined by the "creep" of the blade caused by the continual expansion through heating. Refer to Chapter 4. Sooner or later the blades will hit the turbine casing if the correct time/life cycle is not carefully followed. The manufacturer runs rigorous tests to determine the overhaul cycle, based on maximum temperatures for each phase of flight.

Strict temperature limits will apply to all phases of engine operation. The most stringent limits will be placed on the engine during the start phase, as this is when the airflow through the engine is at its lowest, and the most potential for damage is greatest. Higher limits will apply for take-off as both mass airflow and the need for maximum power will be greatest. There will also be a requirement for a maximum continuous temperature to which the turbine can be subjected, to allow for contingency situations such as engine failure. It is imperative that pilots adhere strictly to temperature limits and report any over-temperatures immediately. Operating the engine as cool as possible within the constraints of operational flexibility will greatly increase engine life and reduce the chance of early failure.

RPM is also a very important parameter, as the speed of the engine for all phases of operation is critical. Typically, the engine will be limited to a set RPM for ground idle, take-off, cruise and descent. It is important to realise that the compressor blades suffer from the same problem as the propeller tips or the wing tips at speeds close to or above the speed of sound. It is therefore extremely important that the rotational velocity of the compressor be maintained within prescribed limits to ensure the operational efficiency of the compressor. Operation outside these RPM limits will also cause undue stress on the other systems on the engine.

Thrust indications, regardless of whether they are indicated in EPR, N_1 or Shaft Horsepower, are particularly important during take-off and cruise, as they are the only indication of the power being produced by the engine. They also indicate that the engine is operating at or near its maximum power, and as such should be limited in time to prevent damage. These limits normally apply for 5 minutes after take-off and 10 minutes during flight with one engine inoperative.

FLAT RATING

It is common practice to flat rate the thrust developed by the engine to a standard day temperature. That is, limit the maximum thrust to a standard day condition thereby reducing the engine turbine exposure to high temperatures. Flat rating usually only applies to take-off where the thrust is held constant over a range of low temperatures. Flat Rating is one of the ways engine life can be extended on modern Turbofan Engines. Refer to Figure 8-7.

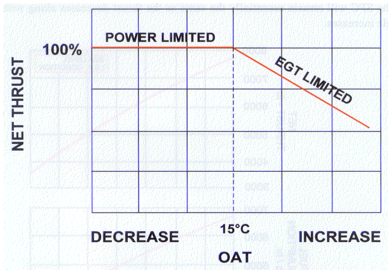

Figure 8-7 Flat Rating

When an engine is Flat Rated, the excess thrust below the temperature used for the calculation, (normally 15°C) is not available even in an emergency.

COMPRESSOR STALL OR SURGE

For a gas turbine engine to operate efficiently, the airflow supplied from the air intake must pass through all the compressor stages at the optimum angle of attack. This angle of attack is a function of the velocity of the axial flow, and the speed of rotation of the compressor blades for a given incidence. Thus, the engine manufacturer is able to optimise engine's performance for one condition of mass flow, pressure ratio and RPM. Outside this design condition it is possible to vary the airflow beyond a critical angle, and stall the compressor blades.

It is possible with the engine operating at low RPM, for the early stage compressor blades to suffer a stall. At low RPM, there is a reduced mass airflow to the compressor, causing the low pressure blades to have a larger angle of attack than the high pressure blades. A slight stall such as this occurs frequently and is not harmful. It may go undetected with the blades becoming unstalled with an increase in RPM.

A Compressor Stall at high RPM is potentially more serious. With the compressor operating at high RPM, the angle of attack through all stages is more or less equal. Any disturbance in mass airflow may cause a stall in all the compressor stages, which may be referred to as a surge.

Such a disturbance would most likely be caused by one of the following;

- icing conditions,
- ingestion of foreign matter
- mechanical breakup,
- abrupt flight manoeuvre, and
- crosswind take-off (S Duct Engine).

A Compressor Surge arises when there is a complete breakdown in the smooth mass airflow through the engine. The value of airflow and pressure ratio at which a surge occurs is called the surge point. During normal operation, a compressor runs at airflow and compression ratio values sufficiently below the surge point, so providing a safety margin. Refer to Figure 8-8.

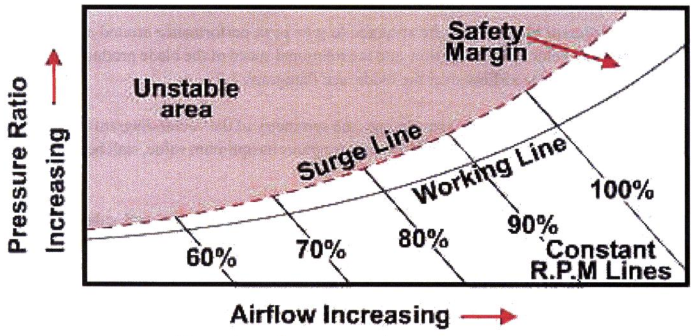

Figure 8-8 Surge Line

An indication of compressor stall or surge will be given by one or all of the following:

- a rise in turbine gas temperature (TGT), or exhaust gas temperature (EGT),
- loss of thrust, with an accompanying yaw,
- fluctuating or falling RPM,
- fluctuating fuel flow, and
- a loud rumbling noise from the engine.

The effects of compressor stall or surge are likely to be:

- loss of engine power,
- severe engine vibration,
- engine flame-out
- excessive EGT, and
- flame from the exhaust or in extreme cases, the intake. Refer to Figure 8-9.

Figure 8-9 C17 Surging in Reverse

Crew Actions for a compressor stall or surge are limited to;

- Reducing engine power to idle, and
- Shutting the engine down if the condition persists.

PREVENTION OF A STALL OR A SURGE

These conditions are controlled by the EEC in early turbofans and the FADEC in modern engines. The FADEC will be covered in more detail later in this chapter.

The two most common methods employed to prevent a stall and surge are the use of;

- Compressor bleed valves, and
- Variable inlet guide vanes (VIGVs)

Compressor Bleed Valves are normally fitted to control the speed of the engine spools by off-loading air from the compressor. The bleed valves are fitted at various stages of the compressor to assist in maintaining a smooth airflow at all operating RPM. Refer to Figures 8-10.

Multiple spool compressor arrangements give an increase in operational flexibility, as each spool is driven by an independent turbine. These engines can operate over a much wider range of conditions, without stalling, than a single spool compressor.

In multi-spool engines, intermediate compressor stage bleed valves open and close at high operating RPM and help control the speed of the high stage compressor when power changes are made. These valves open and close in response to signals from compressor RPM, the fuel control unit and power levers.

<u>Start and acceleration bleed valves are fitted to the higher stages of the compressor. They operate to off-load air from the compressor during start/low rpm operations when airflow and pressure are at their lowest.</u> This assists the high pressure compressor to accelerate quickly and prevents excessive buildup of pressure at the back of the compressor, so helping prevent stall or surge.

It should be noted that any malfunction in the bleed valve system will cause a loss of power from the engine, and may in some instances cause a complete loss of power from the engine.

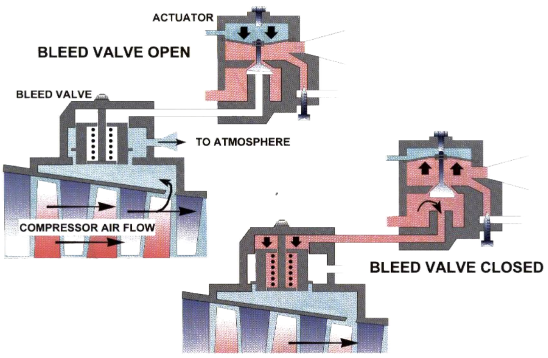

Figure 8-10 Compressor Bleed Valves

Variable Inlet Guide Vanes (VIGV) fitted to the early compressor stages to provide optimum airflow to the compressor rotors at low RPM and changing intake angles. At low RPM, these vanes move towards the closed position to guide the airflow onto the compressor at the correct angle to prevent stalling of the LP compressor. They are positioned by hydraulic/fuel actuators moving in response to signals from the fuel control unit, which are generated by varying air pressure signals from within the engine. This system provides much greater control over compressor airflow, and greatly improved engine efficiency. Refer to Figure 8-11

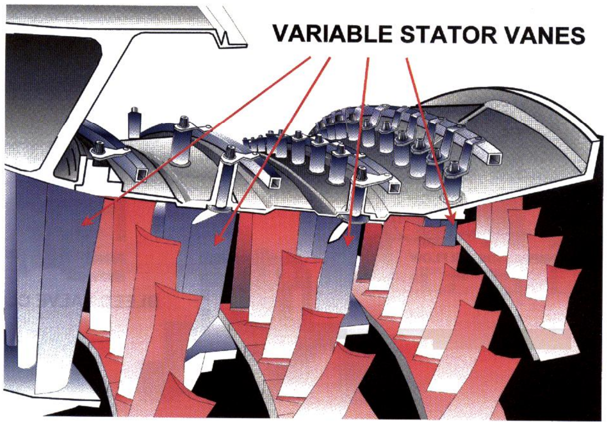

Figure 8-11 Variable Inlet Guide Vanes

FULL AUTHORITY DIGITAL ELECTRONIC CONTROL (FADEC)

Originally, engine control systems consisted of simple mechanical linkages controlled by the pilot, but then evolved and became the responsibility of the third crew member, the flight engineer. By moving thrust levers directly connected to the engine, the pilot or the flight engineer could control fuel flow, power output, and many other engine parameters.

The FADEC eliminates the need for a fuel control unit, using electronics to schedule the amount of fuel required.

To achieve this control the FADEC needs certain inputs, these include;

- Thrust lever position,
- Air Data Computer,
- Flap/slat position, and
- Ground air sensing.

A comprehensive schematic of FADEC inputs is shown on Figure 8-13.

The FADEC has the same functions as the EEC, but has many other features, two of which have already been discussed. Other features include;

- Controlling internal cooling airflows, Refer to Chapter 6.
- Active Clearance Control,
- Fuel heating and oil cooling, and
- Engine monitoring, self testing and fault isolation.

CONTROL OF THRUST

One of the basic purposes of FADEC is to reduce flight crew workload, particularly during critical phases of flight. A typical civilian transport aircraft flight may illustrate the function of a FADEC. The flight crew first enters flight data such as wind conditions, runway length, or cruise altitude, into the flight management system (FMS). The FMS uses this data to calculate power settings for different phases of the flight. At takeoff, the flight crew advances the thrust levers to a predetermined setting, or opts for an auto-throttle takeoff if available. The FADECs now apply the calculated takeoff thrust setting by sending an electronic signal to the engines; there is no direct linkage to open fuel flow. This procedure can be repeated for any other phase of flight.

In flight, small changes in operation are constantly made to maintain efficiency. Maximum thrust is available for emergency situations if the thrust lever is advanced to full, but limitations can't be exceeded. The flight crew has no means of manually overriding the FADEC.

ADVANTAGES

The FADEC has many advantages over the older mechanical and EEC systems. They include;

- Better fuel efficiency,
- Automatic engine protection against out-of-tolerance operations,
- Safer as the multiple channel FADEC computer provides redundancy in case of failure,
- Care-free engine handling, with guaranteed thrust settings,
- Ability to use single engine type for wide thrust requirements by just reprogramming the FADECs,
- Provides semi-automatic engine starting,
- Better systems integration with engine and aircraft systems,
- Can provide engine long-term health monitoring and diagnostics,
- Number of external and internal parameters used in the control processes increases by one order of magnitude,
- Reduces the number of parameters to be monitored by flight crews,
- Due to the high number of parameters monitored, the FADEC makes possible "Fault Tolerant Systems" (where a system can operate within required reliability and safety limitation with certain fault configurations).
- Can support automatic aircraft and engine emergency responses (e.g. in case of aircraft stall, engines increase thrust automatically).

DISADVANTAGE

Full authority digital engine controls have no form of manual override available, placing full authority over the operating parameters of the engine in the hands of the computer. If a total FADEC failure occurs, the engine fails. In the event of a total FADEC failure, pilots have no way of manually controlling the engines for a restart, or to otherwise control the engine. As with any single point of failure, the risk can be mitigated with redundant FADECs.

SAFETY

With the operation of the engines so heavily relying on automation, safety is a great concern. Redundancy is provided in the form of two or more, separate identical digital channels. Each channel may provide all engine functions without restriction. FADEC also monitors a variety of analog, digital and discrete data coming from the engine subsystems and related aircraft systems, providing for fault tolerant engine control.

ACTIVE CLEARANCE CONTROL

This system is used on both the compressor and turbine sections. Air from the low pressure compressor is ducted around the high pressure compressor to ensure the whole compressor is at an even temperature.

Turbine Active Clearance Control starts operating after take-off and climb because during these operations the turbine blade clearance must be greater than it is in cruise. During cruise operation, air flows through cooling ducts around the turbine case and the resultant cooling shrinks the case to minimize blade tip clearances, thus increasing the turbine's effectiveness and saving fuel. Refer to Figure 8-12.

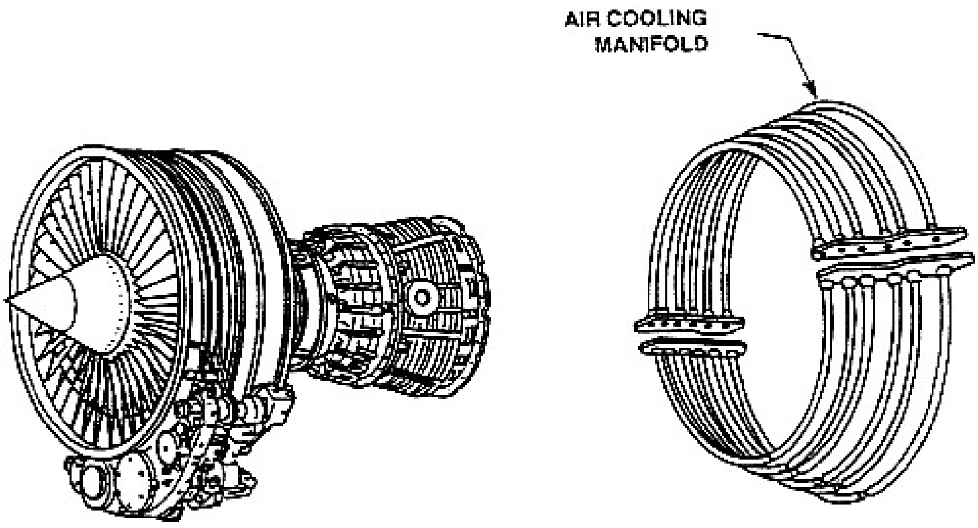

Figure 8-12 Active Clearance Control

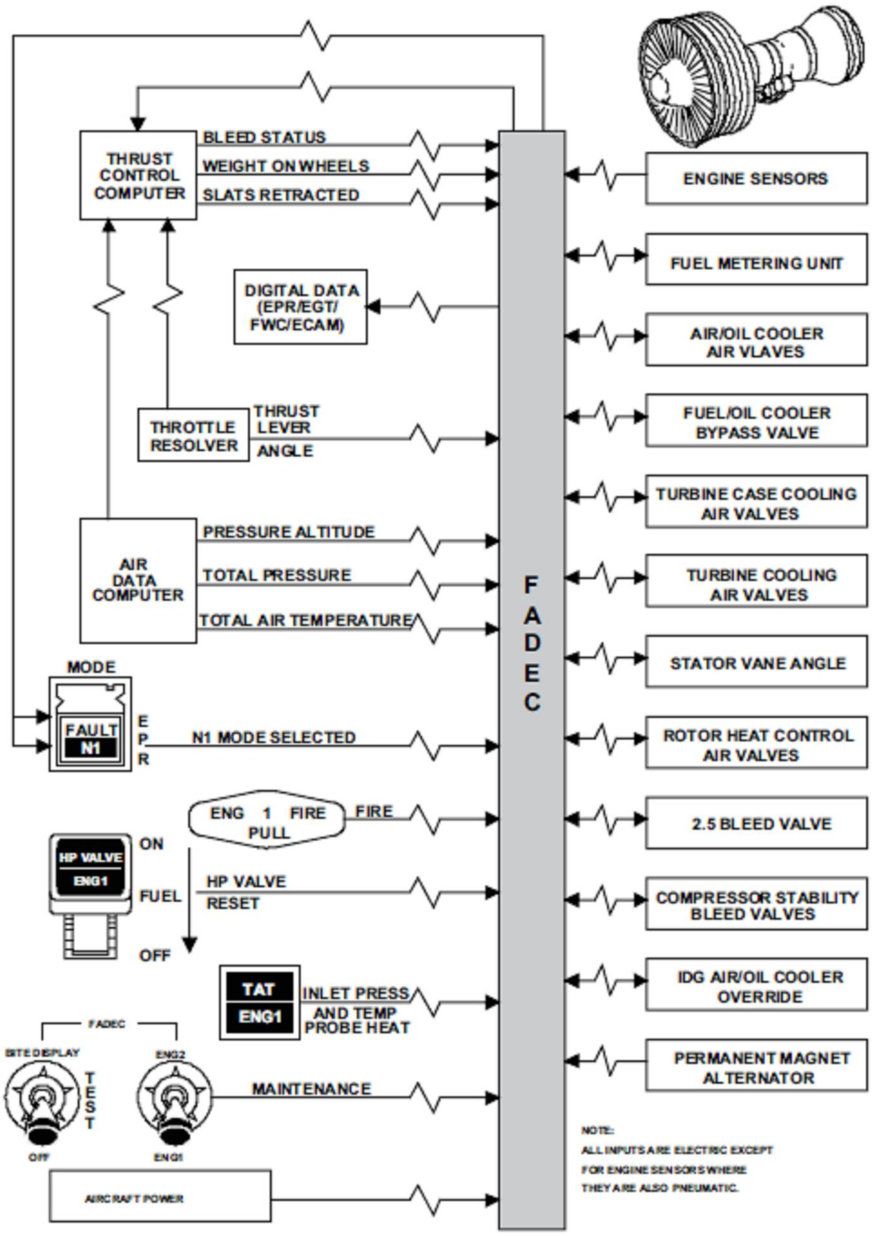

Figure 8-13 FADEC Inputs and Outputs