JET ENGINE CONTROL, IMPLEMENTATIONS

In one form or another, jet engines power all but the smallest airplanes and helicopters. They produce propulsive thrust from the thermal energy of jet fuel. Sir Frank Whittle (1) is credited with developing the first jet engine during the 1930s. It was similar to the turbosupercharger that had been developed in the 1920s, which also used a single-stage centrifugal compressor, a combustor, and a single-stage turbine. Apparently unaware of Whittle's work, a jet engine was also patented in Germany by Hans von Ohain and Max Hahn (2,3) in 1936. The subsequent German development led to the JUMO 109 engine, which had many design features of more modern engines, such as a multistage axial compressor, turbine blade cooling, and a variable-area exhaust nozzle. Unfortunately, it was limited by available materials to an operating life of about 10 hours.

Feedback control has been as essential part of a jet engine from the beginning. Engines are most effective when they can be operated at or near their mechanical or aerothermal limitations, such as rotor speeds, turbine temperatures, internal pressures, and so on. Controlling at but not exceeding a limit is a very important aspect of engine control, which must, therefore, provide both regulation and limit management. Minimum control requirements include a main fuel control for setting and holding steady-state thrust, with fuel acceleration and deceleration schedules to provide transient limit protection. More advanced controls schedule variable engine geometry and augmentor fuel, provide fan and booster stall protection, control variable parasitic engine flows, improve integrated engine-airframe performance, and provide engine health monitoring and diagnostics.

It should be noted that only recently have electronic computers been used to implement engine controls. This is primarily due to the inherent need for safe operation and the harsh temperature and vibration environment in which the computer operates. Many engines in use today are controlled by a hydromechanical controller commonly referred to as an HMU. These are ingenious mechanical computers, which implement the desired control strategy in terms of cams and mechanical integrators. Of necessity, the implemented control strategies must be fairly simple. A drawing of a typical HMU is shown in Fig. 1. More detailed discussions of their operation can be found in (4).

The changeover to electronic controllers began in the 1980s as rugged integrated circuits became available and as the need for improved performance led to increased functionality and tighter control. Pratt and Whitney calls its controller a Digital Engine Control (DEC), while General Electric calls it a Full Authority Digital Electronic Control (FADEC). These are highly customized computers, whose complexity depends mainly on the number of sensor inputs and actuator outputs. Such electronic controllers result in higher engine operating efficiencies, by allowing tighter engine control through the use of higher loop gains and improved strategies to reduce transient overshoot or undershoot. It also allows implementation of control algorithms, which would be difficult to implement mechanically.

BASIC ENGINE TYPES

Three basic types of jet engines are in current use:

1. Turbojets
2. Turbofan engines
3. Turboprop/turboshaft engines

The turbojet was the earliest form of jet engine, and is the simplest of the three. Its major components include a compressor, combustor, turbine (which drives the compressor), and exhaust nozzle. It produces a relatively high specific thrust, defined as thrust per kilogram of airflow. It is the best type of engine for high subsonic and supersonic flight speeds.

The turbofan uses a turbojet for its core and adds a fan in front of the core compressor and a second power turbine behind the core turbine, to drive the fan, as shown in Fig. 2. The flow capacity of the fan is designed to be substantially larger than the compressor, so that the excess air can be bypassed around the core and exhausted through a separate nozzle. The bypass approach reduces engine specific thrust, but increases propulsion efficiency, thereby reducing fuel consumption and is the engine of choice for subsonic commercial airplanes.

The turboprop or turboshaft engine includes the turbojet core and power turbine, but has no fan. Its power turbine can drive an external propeller or helicopter rotor through a gear

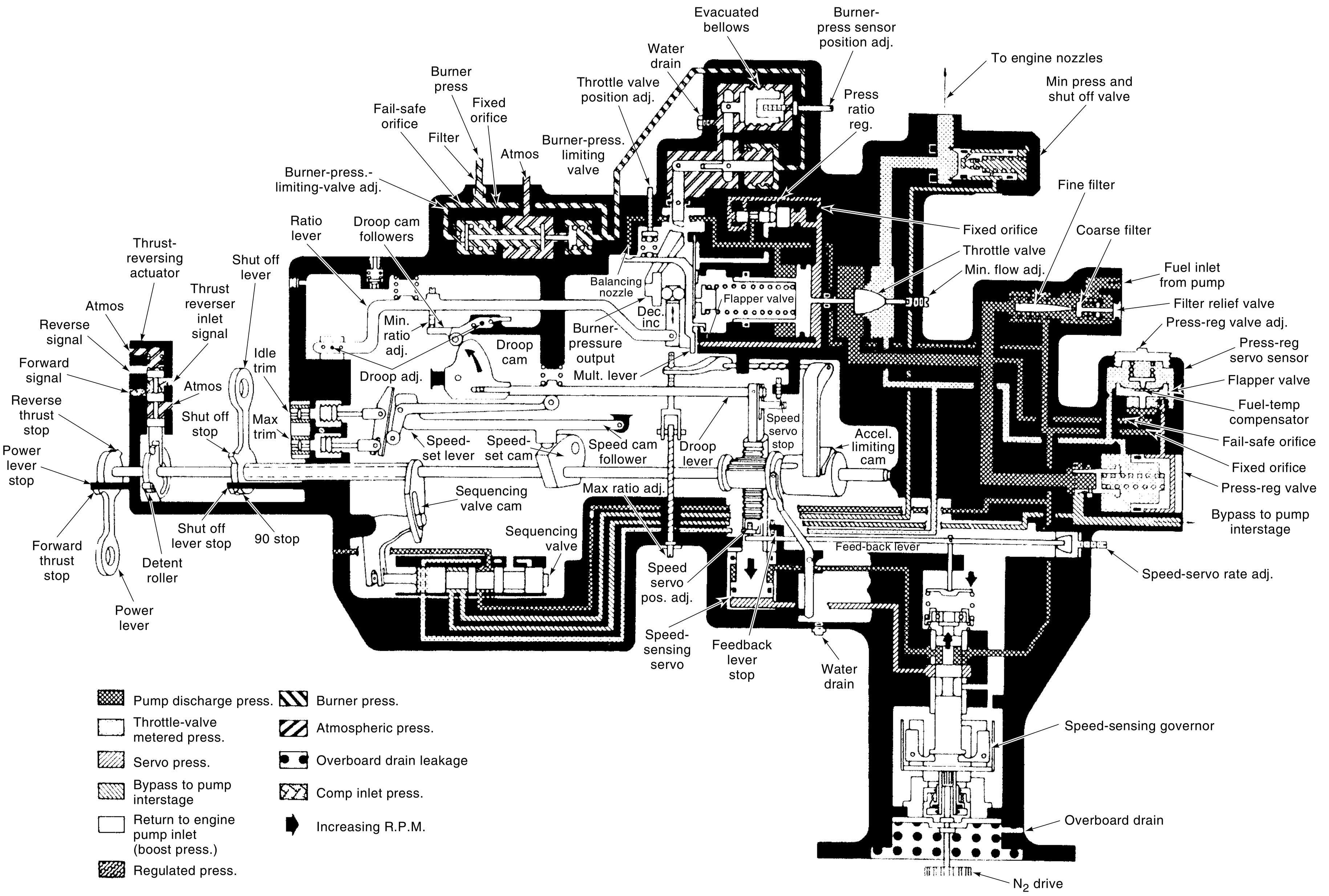

Figure 1. Hydromechanical controller—Hamilton Standard JFC25 (4).

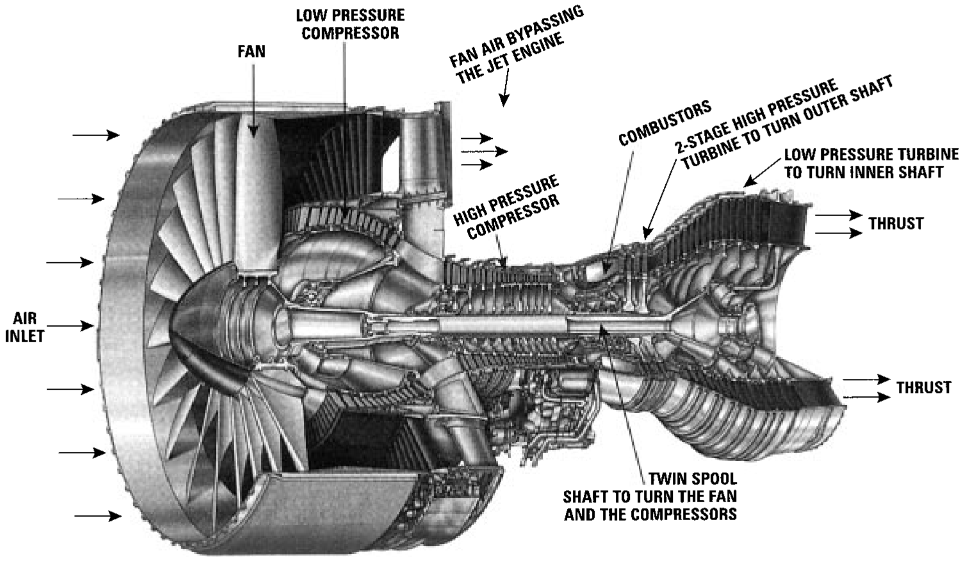

Figure 2. Pratt & Whitney PW4084 turbofan engine.

reduction unit. The rotor or propeller further increases total engine air flow, decreases specific thrust, and increases propulsion efficiency. The turboshaft is the best type of powerplant for helicopters and small, lower speed aircraft.

Variations of the above basic engine types can include:

- Dual rotor core engines containing two compressors and two turbines
- Turbofans with a booster compressor between the fan and core compressor for supercharging the core
- Mixed-flow turbofans which mix the bypass and core discharge flows and exhaust both through a single nozzle
- Turbojet augmentors, turbofan fan burners, and mixed flow augmentors for increasing engine thrust for better takeoff, transonic acceleration, or combat capabilities

SIMPLIFIED ENGINE THEORY

The most common form of jet engine is the high bypass ratio turbofan. It will be described in this article. More detailed discussion on engine design and operation can be found in (5,6). A turbofan engine bypasses a substantial fraction of the inlet air around the hot section or core of the engine, in order to achieve a high propulsive efficiency. A simplified diagram of such an engine is shown in Fig. 3.

The numbers in Fig. 3 refer to standardized (5,7) engine station locations:

0	Freestream ambient air conditions
1	Inlet entry
2	Fan entry
25	High-pressure compressor entry
3	High-pressure compressor exit
4	Burner exit/high-pressure turbine entry
45	High-pressure turbine exit/low-pressure turbine entry
5	Turbine exit
8	Nozzle throat
9	Exhaust nozzle exit

Double-digit numbers 12–18 are used for bypass flow stations from fan tip entry (station 12) through the bypass duct to the bypass nozzle (station 18).

Reciprocating automobile engines operate on a four-stroke Otto cycle. Their internal combustion process achieves extremely high pressures through constant volume combustion, which results in a high power per kilogram of air flow.

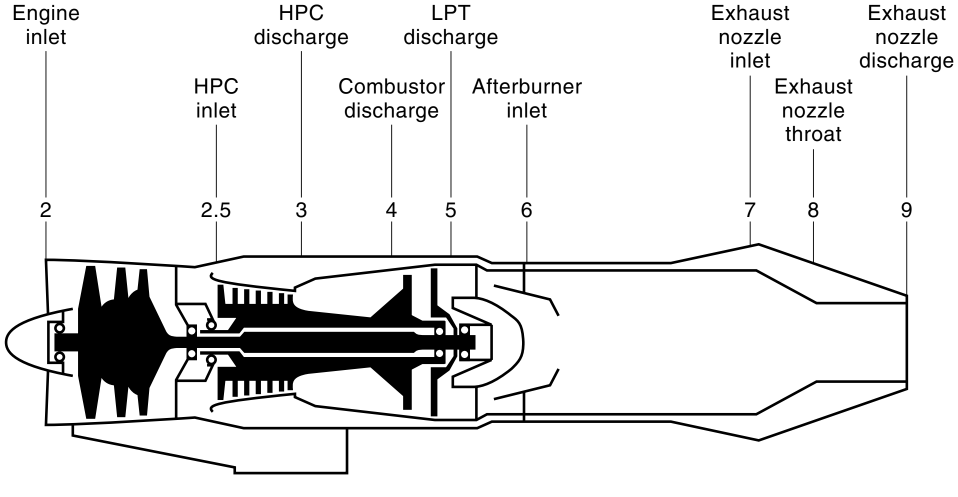

Figure 3. Engine station locations.

Conversely, the jet engine operates on a continuous flow Brayton cycle, which ideally involves isentropic compression and constant pressure combustion. It operates at a substantially lower maximum temperature and pressure than the Otto cycle. Figure 4 shows pressure-volume and temperature-entropy (TS) diagrams for the ideal Brayton cycle. It is the basis of the turbojet engine and the core of the turbofan. It contains the following thermodynamic processes:

0–2	Isentropic compression in the engine inlet
2–3	Isentropic compression in the engine fan, booster, and compressor
3–4	Constant pressure heat release in the combustor
4–5	Isentropic expansion in the high-pressure and low-pressure turbines
5–9	Isentropic expansion to atmospheric pressure in the exhaust nozzle

An isentropic process means that there is no temperature raise and the process is reversible. Hence entropy is constant. The actual cycle involves near isentropic compression and expansion processes, a pressure loss in the combustor, and an incomplete expansion to near-atmospheric pressure in the exhaust system. Total temperatures and pressures, which include the effect of the air velocity, are used for all internal engine conditions.

Alternative options, which include the turbojet, turboshaft, and turbo-augmented cycles, will not be discussed, but can be determined from similar techniques. The following sections describe each of the turbofan engine processes in more detail.

Inlet Compression

Air flow is supplied to the engine by the inlet which compresses the inlet air. Assuming that the ambient air pressure, P_0, and temperature, T_0, is not moving and the inlet is moving at the flight mach number, M, the total pressure and temperature at the inlet is:

$$P_2 = \eta_r P_0 \left[1 + \left(\frac{\gamma - 1}{2}\right) M^2\right]^{1/k} \tag{1}$$

$$T_2 = T_0 \left[1 + \left(\frac{\gamma - 1}{2}\right) M^2\right] \tag{2}$$

where P is pressure, T is temperature, M is flight Mach number, γ is the specific heat ratio of air (constant pressure specific heat/constant volume specific heat), k is the ratio $(\gamma - 1)/\gamma$, and η_r is the ram recovery (actual total pressure/ideal total pressure) which is approximately 1 for subsonic flight.

Compression System

The turbofan compression system consists of a fan, a booster, and one or more compressors. Operating characteristics of each are a function of their inlet total temperature and pressure, rotational speed, and discharge pressure. It is convenient to normalize flow and speed with respect to inlet temperatures and pressures. The following corrected parameters can be used to represent operating characteristics independent of the actual inlet temperature and pressure levels:

- Corrected flow ($W\sqrt{\theta_a}/\delta_a$)
- Corrected speed ($N/\sqrt{\theta_a}$)
- Pressure ratio (P_b/P_a)
- Adiabatic efficiency (η_c)

where W is the flow rate, θ is the inlet temperature divided by the ambient standard sea level temperature, δ is the inlet pressure divided by the ambient standard sea level pressure, N is the compressor rotational speed, and η_c is the compressor adiabatic efficiency. The subscripts a and b refer to inlet and discharge conditions, respectively, for the fan, booster or compressor.

Operating characteristics of a typical compressor are shown in terms of the above corrected parameters in the compressor map in Fig. 5. Given measured corrected speed and pressure ratio, one can determine corrected flow and efficiency (not shown in Fig. 5). Exit temperature and required work can then be obtained from:

$$T_b = T_a \left[1 + \frac{(P_b/P_a)^k - 1}{\eta_c}\right] \tag{3}$$

$$\mathrm{HP} = W_a c_p (T_b - T_a) \tag{4}$$

where HP is the work required to drive the compressor and c_p is specific heat of air at constant pressure. This work is expended heating the air from T_a to T_b.

Compressor characteristics must be obtained from extensive testing of individual stages, the full compressor, and sometimes the entire engine.

Stable compressor operation is limited to the region below the compressor stall line shown in Fig. 5. Two modes of instability can occur: *surge,* which is a longitudinal flow oscillation over the length of the compressor and turbine, and *stall,* which is the lack of pressure rise between the compressor blades. Often stall occurs at low rotor speeds and surge at high rotor speeds. Both surge and stall generate violent axial oscillations of the internal air column, which can cause sub-

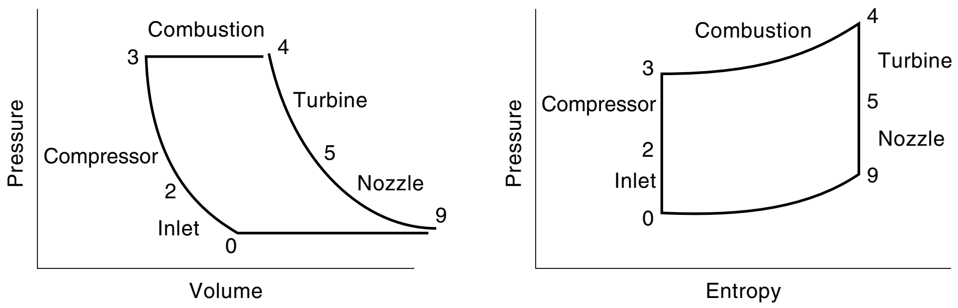

Figure 4. Pressure-volume and temperature-entropy (TS) diagrams for turbojet.

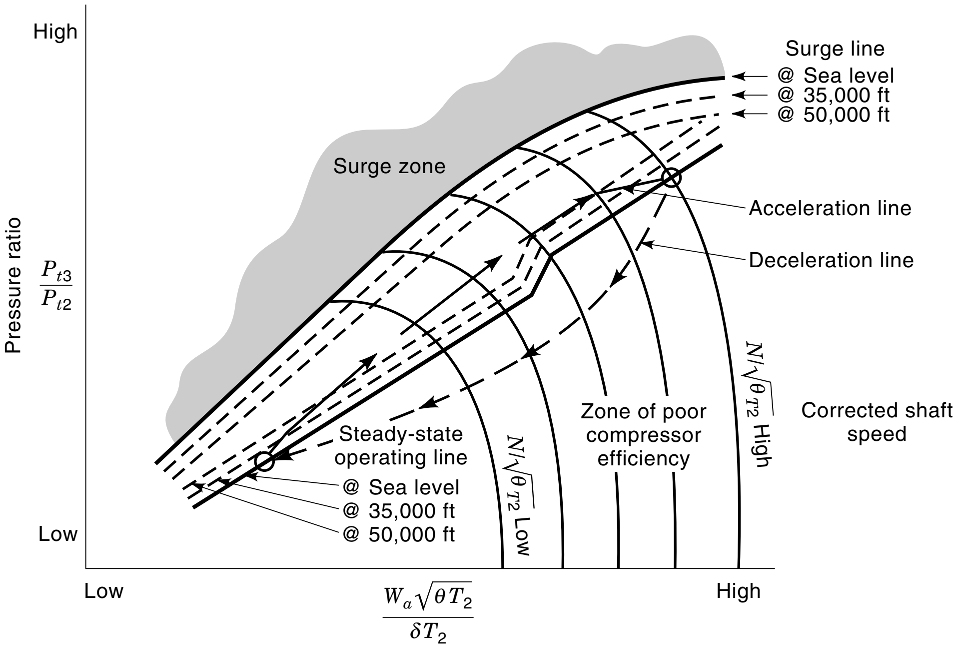

Figure 5. Engine compressor map.

stantial damage to both the compressor and the engine. Fan stalls can be caused by operation with too small a fan duct nozzle area, booster stalls by a throttle reduction to a lower engine rotational speed, and compressor stalls by a rapid throttle increase. The engine and control system must be designed to avoid surge/stall, with sufficient design margin to offset the effects of altitude, increased tip clearances, component deterioration, and engine/airflow operation at high angles of attack.

Combustion System

Fuel is burned in the combustor at a slight pressure drop, and the resulting products of combustion are expanded in the turbines. The required fuel flow can be obtained from:

$$W_f = \frac{W_4 c_p (T_4 - T_3)}{Q_f \eta_f - c_{pf} T_4} \tag{5}$$

where W_f is the fuel flow rate, Q_f is the higher heating value of the fuel, and η_f is the combustion efficiency. The subscript 4 refers to high-pressure turbine inlet conditions. Depending on the combustor pressure, the combustor will operate only in certain regions, as shown in Fig. 6. The high-temperature blowout region is referred to as *rich blowout* and the low temperature region is referred to as *lean blowout.*

The total gas flow downstream of the combustor is the sum of the air flow and the fuel flow. The specific heat of the gas mixture can be obtained from the equation:

$$c_{pg} = \frac{c_{pa} + f \cdot c_{pf}}{1 + f} \tag{6}$$

Other mixture properties, such as enthalpy and entropy but not γ can be obtained by a similar process.

A significant amount of air is required to cool the combustor liner, but it is returned to the gas stream prior to the turbine.

Turbine Expansion

The turbine expansion system provides the power to drive the compression system. The high-pressure turbine drives the compressor through the high-pressure shaft, and the low-pressure turbine drives the fan and booster through the low-pressure shaft. The operating characteristics of each turbine are defined in terms of the following corrected parameters:

- Corrected flow function ($W_{ga}\sqrt{T_a}/P_a$)
- Corrected speed ($N_a/\sqrt{T_a}$)
- Temperature ratio [$(T_a - T_b)/T_a$]
- Adiabatic efficiency (η_t)

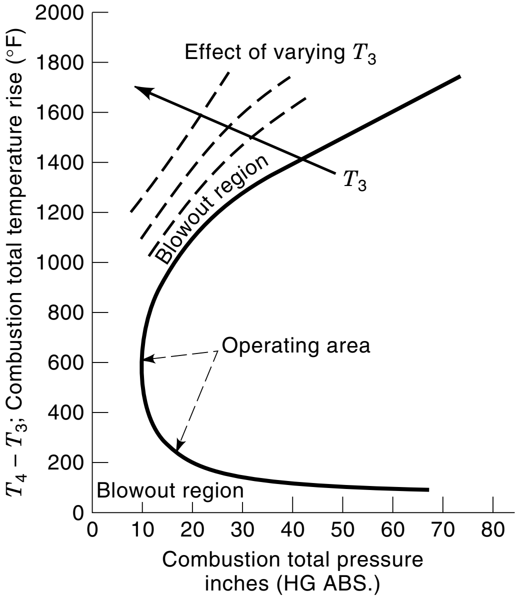

Figure 6. Combustor blowout limits.

The subscripts a and b refer to inlet and discharge conditions, respectively, for the high-pressure and low-pressure turbines. Operating characteristics of a typical turbine are illustrated, in terms of the above corrected parameters, in the turbine map shown in Fig. 7. Given measured corrected speed and temperature ratio, one can determine corrected flow and efficiency. Note that the turbine inlet flow is choked at a constant value over a large part of the operating range.

The temperature ratio across the turbine can be obtained from the required work of the compressor (for the high-pressure turbine) or the work of the fan and booster (for the low-pressure turbine):

$$\left[\frac{T_a - T_b}{T_a}\right] = \frac{HP}{W_{ga} c_{pg} T_a} \tag{7}$$

Bypass Duct

A fraction of the fan discharge air is bypassed around the engine core, and exhausted through either a separate bypass nozzle, or mixed with the core stream and exhausted through the core nozzle. In either case, the bypassed air improves the propulsive efficiency of the engine, and makes it the preferred approach for the world's large commercial fleet. The bypass ratio is defined as:

$$\text{Bypass ratio} = \frac{\text{Total fan inlet air flow}}{\text{Core inlet air flow}} \tag{8}$$

It represents a major turbofan engine design parameter. The bypass duct operates with a slight pressure drop of about 5 percent of the fan discharge pressure and no loss in total temperature.

Exhaust System

The core and bypass streams are expanded through core and bypass nozzles to the pressure of ambient air. A converging nozzle can be used for exhaust flow, which is either subsonic or sonic, and a converging-divering (C-D) nozzle would be required for supersonic flow. The throat or minimum area of the nozzle will regulate the amount of flow that can be exhausted through the nozzle. The required throat area for the core stream can be obtained from:

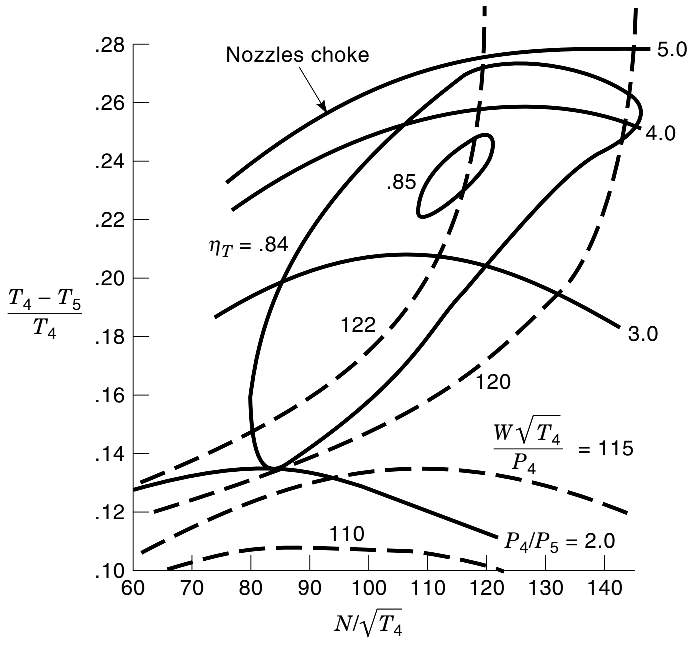

Figure 7. Turbine map.

$$A_8 = \frac{W_{g8}\sqrt{T_8}}{\omega_8 N_8 P_8} \tag{9}$$

where ω_8 is the sonic flow function and N_8 is the ratio of flow to sonic flow:

$$\omega_8 = \sqrt{\gamma g/R} \tag{10}$$

$$N_8 = M_8\left[\frac{1.2}{1 + .2M_8^2}\right]^3 \tag{11}$$

The throat Mach number must be 1 if the nozzle total-to-static pressure ratio is greater than the critical value of about 1.8. If the pressure ratio is less than critical, the throat Mach number will be less than 1, and can be obtained from the relationship:

$$M = \sqrt{\left(\frac{2}{\gamma - 1}\right)[(P_T/P_O)^k - 1]} \tag{12}$$

The exit area will effect the thrust output of the engine. Similar equations can be used for the bypass or mixed flow streams.

Augmentor

Military engines generally have an augmentor, either behind the low-pressure turbine or in the bypass duct. Augmentors are sometimes referred to as *afterburners.* They are used to increase engine thrust for selected segments of the flight, such as takeoff, climb, acceleration to supersonic speed, or combat. Augmentation is a relatively inefficient approach for generating thrust. This penalty can be minimized by maintaining the engine at its maximum nonaugmented setting, thereby minimizing the thrust increment provided by the augmentor.

Augmentation requires a variable exhaust nozzle. The reason can be seen from Eq. (9). For a fixed A_8, an increase in T_8 must be offset by an increase in P_8. Since combustion is essentially a constant-pressure process, the increase in P_8 results in an increase in turbine pressure, P_5 and, hence, an increase in P_3, moving the engine operating line closer to stall. From Eq. (7), the increase in P_5 also produces less work from the turbine, which will reduce core rotor speed. The control system will increase main fuel flow, to keep rotor speed constant, resulting in increased temperature of the turbine. Thus A_8 must be opened to maintain a constant P_8, to avoid compressor stall and overtemperature of the turbine.

Engine Trade-Offs

Engine operating characteristics are set predominantly by four interacting design variables: (1) bypass ratio, (2) turbine inlet temperature, (3) overall pressure ratio, and (4) fan pressure ratio. The best design choice will be dependent on the intended application or mission, the level of technology available, the degree of subsequent growth capability required, and expected competition from other engines.

Bypass ratio will have the most dominant effect on engine performance. High bypass ratios of 4 to 8 are used for most large commercial engines. Increased bypass ratio will improve (decrease) specific fuel consumption (SFC) at cruise, and improve specific thrust (thrust per kilogram/second of air flow) at takeoff. Ultra-high bypass ratios of 10 to 20 have been considered for improved cruise performance, but would require an unducted fan (8) or reduction gears between the fan and low-pressure turbine. Lower bypass ratios of 1 to 3 provide improved thrust for flight Mach numbers of 1 to 2, and are used for military fighters and bombers. A pure turbojet has a zero bypass ratio, and would be used for supersonic transport.

High turbine inlet temperature leads to improved specific thrust and a lighter engine, but requires more expensive turbine materials and a more complex turbine cooling system, which reduces cruise performance. The proper balance will depend on the relative importance of specific thrust, which sets engine size, and weight and cruise performance, which sets fuel requirements. Military applications will tend to demand higher temperatures, to achieve a lighter engine weight, while commercial applications will place a stronger emphasis on cruise performance.

Overall pressure ratio, which is the compressor discharge pressure divided by fan inlet pressure, will affect both takeoff and cruise performance. Optimum pressure ratio tends to increase will increased turbine inlet temperature, but decreases as flight Mach number increases. Pressure ratios of 40 : 1 and 50 : 1 could be effective with modern temperatures at takeoff, but should be limited to the 10 : 1 to 15 : 1 range at supersonic speeds. Extremely high-pressure ratios would require the use of high alloy steel or titanium at the rear of the compressor, and cooled-cooling air for use in the high-pressure turbine.

High fan pressure ratio improves takeoff performance, but increases exhaust noise. The achievable pressure ratio will be dependent on the work available from the low-pressure turbine. Both will be dependent on turbine inlet temperature and overall pressure ratio. Fan pressure ratios of 2 to 3 can be achieved on low bypass military engines, but would be limited to the 1.6 to 2.0 regime for high bypass commercial engines. Mixed-flow turbofans would also require the use of fan pressure ratios that produce duct pressure levels roughly equal to the turbine discharge pressure, in order for mixing to occur.

CONTROL REQUIREMENTS

The overall function of an engine controller is to provide thrust in response to throttle position. It must achieve the requested thrust with the lowest specific fuel consumption. It must also insure that the following limits are not exceeded:

Maximum fan speed
Maximum compressor speed
Maximum turbine temperature
Fan stall
Compressor stall
Maximum compressor discharge pressure
Minimum compressor discharge pressure
Lean burner blowout
Rich burner blowout

For an aircraft turbine engine, it is necessary to achieve maximum thrust with minimum engine weight. This means that all components operate at mechanical or thermal limits for at least one of the engine's critical operating conditions. At other operating conditions, operation at only one or more of the above limits may be required. Figure 8 shows, various typical limits as function of mach number and altitude. The control must directly or indirectly control each limiting parameter and limit engine thrust, so that no limits are exceeded. Engine operation at maximum power will, consequently, require operation at one or more of the engine operating limits. Part power engine operation should occur below all limits and at the lowest specific fuel consumption for the thrust requested.

SENSORS AND ACTUATORS

The pilot controls aircraft speed by setting the throttle position to a thrust which will permit operation at the desired speed. One would like to run the engine directly to the required thrust, by modulating engine fuel flow until the required thrust has been achieved. Similarly, one would like to operate at the fan and compressor stall limits and the turbine inlet temperature limits. However, none of these parameters can be measured directly in flight. Thrust can only be measured in a test cell, where one can establish a stationary reference. Likewise, stall margins are established in test rigs, by actually stalling the fan or compressor. Thus one must select practical measurements that are related to the ideal measurements. These practical measurements must also be relatively immune to engine-to-engine variation due to manufacturing tolerances and engine deterioration. Generally, Monte Carlo

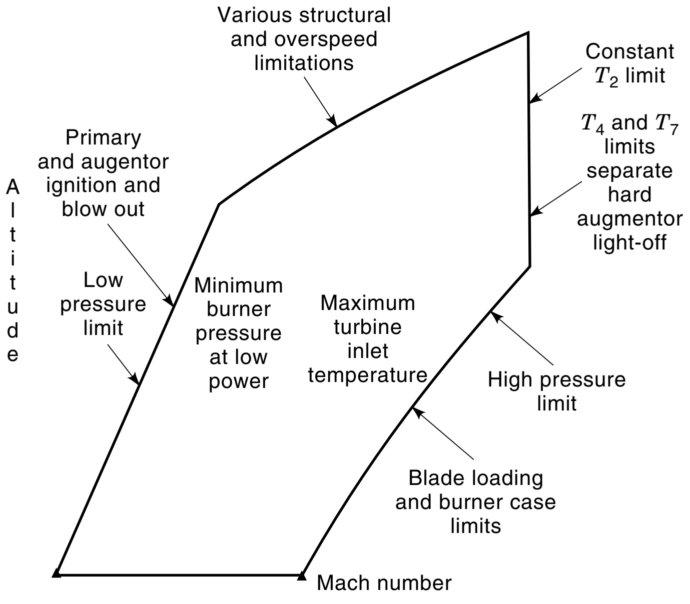

Figure 8. Engine limits (19).

simulations are performed to establish the appropriate selection.

Various thrust setting parameters can be used to set thrust indirectly. GE uses fan rotor speed, Pratt and Whitney uses core engine pressure ratio (EPR), and Rolls Royce uses an integrated engine pressure ratio (IEPR, which is a flow-weighted average of the core and bypass duct pressure ratios).

Commonly selected basic sensors are:

N_1	Fan speed
N_2	Core speed
EPR	Engine pressure ratio = P_5/P_2
W_f/P_3	Fuel flow divided by compressor exit pressure
T_{45}	Low pressure turbine inlet temperature

Three of these are required for the direct determination of the critical overspeed and overtemperature limits. Because of the need to shield the thermocouples, the T_{45} measurement has a slow response time, and is not particularly good for control purposes. Either EPR or W_f/P_3 is used to control the engine. W_f/P_3 is very commonly used and is a natural control parameter. To see why, note that the flow through the turbine is:

$$W_4 = P_4 \cdot \frac{c}{\sqrt{T_4}} \cong P_3 \cdot \frac{c}{\sqrt{T_4}} \tag{13}$$

since there is very little pressure drop across the burner. Therefore

$$\frac{W_f}{P_3} = \frac{W_f}{W_4} \cdot \frac{c}{\sqrt{T_4}} \tag{14}$$

Since the fuel air ratio, W_f/W_4, is directly related to flame temperature and, hence, turbine temperature T_4, so is W_f/P_3. Thus W_f/P_3 provides good control of T_4, good reaction to stall, and good reaction to burner blowout. An added advantage is that W_f/P_3 is relatively easy to sense.

Commercial engines will generally have variable compressor stator vanes, a fuel control valve, and a variable booster bleed valve (if there is a booster). The variable stators are for improving low-speed stall margin and high-speed performance in the core compressor. The booster bleed valve is used to bleed booster air into the bypass duct, to improve booster stall margin at part power and during throttle reductions. Both are generally controlled open-loop. The only closed-loop control in a commercial engine is the main fuel control. Military engines will generally add an afterburner for increasing thrust during takeoff, transonic acceleration, and combat. The afterburner will require both an augmentor fuel control and a variable exhaust nozzle throat area (A_8), to permit a wider range of augmented thrust and to manage interactions with the main fuel control.

ENGINE CONTROLS

Proportional and Integral Control

The simplest and most common type of control is based on a proportional control. With minor variations, it is the basis of all hydromechanical controls, and has been used for some of the earliest electronic controls as well. More recent engines with electronic controls use proportional plus integral control, to minimize errors. The control can be subdivided into a steady-state control and a control for transient operation. The steady-state control, which maintains engine operation along its steady-state operating line, will be discussed first. The transient controls necessary to accelerate and decelerate the engine while meeting stall, flameout, and temperature limitations, will then be added.

A block diagram of the single-input, single-output proportional plus integral control, which maintains the engine at a desired operating point, is shown in Fig. 9. A fan speed demand schedule establishes the desired fan speed as a function of inlet temperature and throttle angle. Fan speed error is determined from the difference between the demand speed and the actual fan speed. A delta W_f/P_3 signal is obtained proportional to the fan speed error. This signal is multiplied by the P_3 sensor signal and the resulting change in fuel flow is used to drive the fuel metering valve. The gain is scheduled as a function of core speed, to meet the control requirements over the entire flight envelop. In an electronic control, the desired fuel flow is computed directly, rather than as a ratio, with P_3. The control will provide the control response for small increases or decreases in throttle angle. Controllers based on EPR or IEPR substitute pressure ratio demand schedules and error signals for the corresponding fan speed parameters.

With proportional control there is always an error or *droop* between the desired speed and the actual speed. As the load on the engine increases, this error will increase. The loop gain is normally made high, to minimize this droop. The use of integral control eliminates this problem.

The throttle schedule is designed to provide thrust as a linear function of the throttle angle. It also maintains the engine at the most efficient operating point possible. Engine thrust can be shown to be a nonlinear function of engine speed. The throttle schedule inverts this nonlinear relationship, to provide the desired speed as a function of throttle angle.

Transient operation is illustrated in Fig. 10. It shows W_f/P_3 as a function of core speed for a variety of engine operating modes during engine accelerations and decelerations. An acceleration will occur when the throttle is advanced to a demand speed higher than the current speed. A min-select strategy will then lead to the following series of processes:

- The positive speed error will result in a proportional W_f/P_3 error, which will open the fuel valve, admitting more fuel to the engine and result in an acceleration from point 1 along the speed governor line to point 2, where it will intersect the maximum fuel ratio line.
- Min-select strategy will switch operation to the maximum ratio line, and it will continue to accelerate to point 3, where it will intersect the compressor surge limit line.
- Min-select strategy will switch operation again, this time to the surge limit line, where it will continue to accelerate at a slower pace to point 4.
- At point 4, the min-select strategy will switch operation back to the maximum fuel ratio line, and the engine will continue to accelerate to point 5.

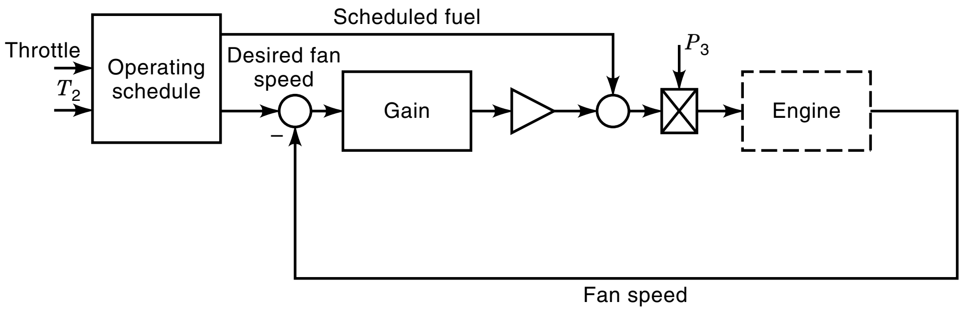

Figure 9. Block diagram of proportional controller.

- At this point, operation will be switched back to the speed governor line, leading to the steady-state operating point at the demanded speed at point 6.
- This final process will reduce W_f/P_3, until the engine stabilizes at point 6.

An engine deceleration will occur when the throttle is retarded to a speed demand lower than the current speed. A max-select strategy during the deceleration will then lead to the following:

- The negative speed error will lead to a proportional W_f/P_3 error, which closes the fuel valve, reduce fuel flow, and cause a deceleration along the speed governor line to point 7.
- Max-select strategy will switch operation at point 7 to the minimum fuel ratio line to point 8.
- Max-select strategy will switch operation again at point 8 to the speed governor line, which will lead back to steady-state operation at point 1.
- Fuel flow will be increased until the engine stabilizes at the demanded speed at point 1.

Note that each of the above lines in Fig. 10 are generally functions of inlet pressure (P_2) and possibly temperature (T_2) as well. To make the engine accelerate or decelerate rapidly and remain as efficient as possible, the control is designed to keep the engine close to or on each limit.

The above processes will occur during large increases or decreases in throttle/speed demand. During small throttle increases, the minimum select process will transition engine operation from the 1–9 speed governor line directly to the 9–10 speed governor line. This will lead to stable operation at point 10. A small deceleration command at point 6 will result in a similar transition at point 11 to stable operation at point 12.

Other limits can be handled in a similar fashion. The deceleration limit provides sufficient fuel to maintain combustion. Except for high flows, it can be independent of speed. An idle speed controller is provided, to maintain minimum engine speed. It is a proportional controller similar to Fig. 9, with no additional schedule and the reference speed is the desired idle speed. Overtemperature and overspeed are also handled as proportional controls, with the maximum temperature or speed as the reference. The overtemperature controller senses T_{45}.

A block diagram of the complete control is shown in Fig. 11.

Ndot Control

A variant of proportional control uses the derivative of rotor speed (9,10) (Ndot or rotor acceleration), rather than rotor speed, to control engine acceleration and deceleration. Direct

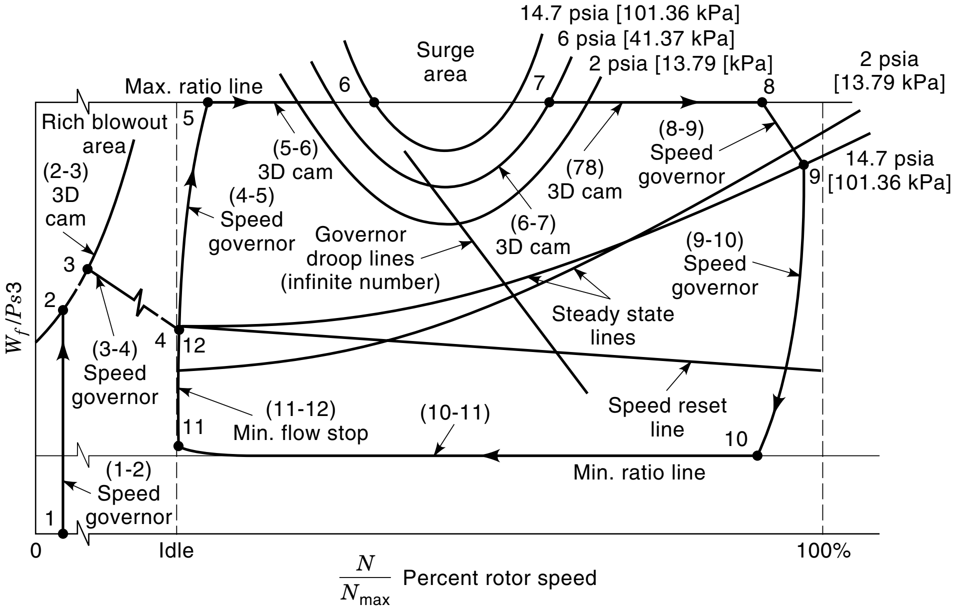

Figure 10. Characteristic controller schedules.

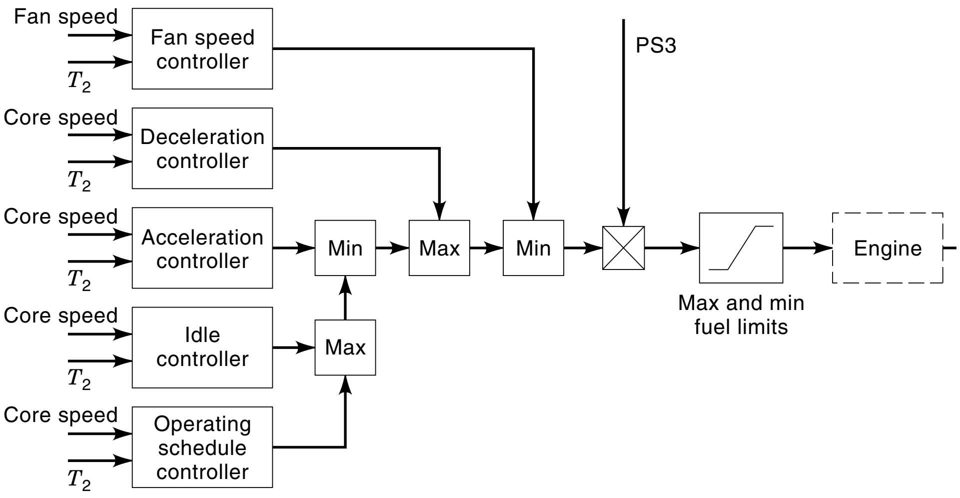

Figure 11. Block diagram of complete controller.

control of acceleration, rather than speed, allows tighter control of engine acceleration, thereby improving transient response and reducing mechanical stress. While rotor acceleration cannot be easily measured directly, a second-order filter applied to speed can be used to give a good approximation. The algorithm shown in Fig. 12 replaces that shown in Fig. 9. The previous acceleration schedule is replaced with one that directly specifies allowable engine acceleration. A lead lag compensator is necessary to improve transient response. The Ndot control will result in a more consistent acceleration between a cold engine that has not been run for at least 30 minutes, and a warm engine that is being reaccelerated in a shorter time.

Fan Speed Control

Throttle position is converted to a specific fan speed requirement as a function of engine inlet temperature, T_2, and inlet pressure, P_2. Fan speed is held to the desired speed by replacing the proportional control with an isochronous integral control. The bandwidth of the loop will determine the speed of response and, hence, how tightly the fan speed is maintained. The core speed “floats,” within limits, at a speed necessary to provide the sufficient power to maintain fan speed.

The agility of a helicopter (11) depends on maintaining rotor speed and, hence, power turbine speed during maneuvers such as a waveoff from an autorotational descent. The load on the rotor is changed by the pilot, changing either the collective or cyclic settings. System responsiveness is determined by the dynamics of the power turbine isochronous governor. Unfortunately, the helicopter rotor first torsional resonance mode limits the bandwidth of the control. Notch filters centered at the rotor resonance are used to allow high crossover and, therefore, a more responsive system.

A further refinement of fan speed control is called *Power Management Control.* This control integrates aircraft and engine requirements, to compute the necessary thrust levels to maintain uniform aircraft speed. The controller uses information on the specific aircraft configuration, inlet pressure, temperature, Mach number, and engine bleeds, to calculate the desired thrust and a reference fan speed or pressure ratio. In order to compensate for engine-to-engine quality variation and deterioration, the pilot then moves the throttle to match the reference fan speed or pressure ratio. Aircraft speed is maintained, during variations in inlet pressure and temperature, by closed-loop adjustment of these reference values.

Multivariable Control

As indicated previously, commercial engines are generally controlled by a single, closed-loop main fuel control. The additional actuators have minimal interactions between each of the open-loop controls and with the main fuel control. Consequently, single-input, single-output design techniques are adequate.

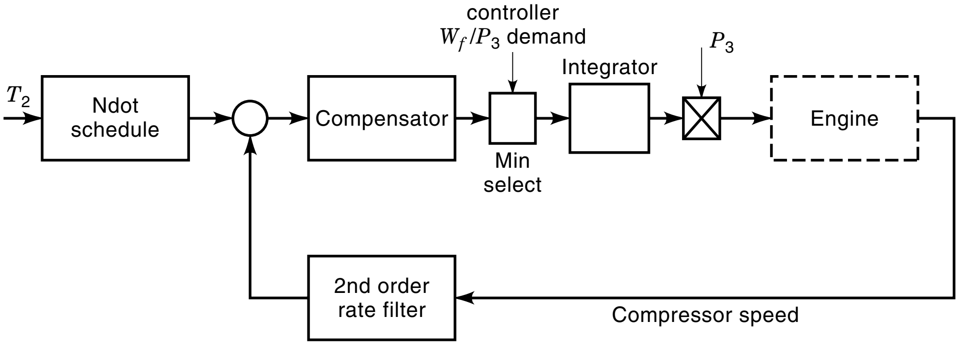

Figure 12. N-dot controller.

This is, however, not the case for military engines, which generally have an afterburner augmentor, to increase engine thrust for selected segments of the flight, such as takeoff, climb, acceleration to supersonic speed, or combat. The augmentor fuel flow will determine augmentor temperature, T_6, which affects engine pressure ratio and turbine temperature. However, the primary combustor fuel control also controls these variables. Thus the augmentor fuel control loop and the combustor fuel control strongly interact. Early design approaches used the concept of spectral separation, which made the combustor fuel control loop an order of magnitude faster than the augmentor control loop. More recent designs have used a multivariable approach, to achieve two control loops of approximately the same response time.

Another application of multivariable control is on a variable cycle engine (VCE), which has a variable area bypass injector, or VABI. The VABI allows the bypass ratio to be changed during flight. When closed, the engine behaves more like a turbojet, providing more thrust during supersonic flight. Opening the VABI makes the engine more like a turbofan, improving specific fuel consumption during cruise.

Much of the published literature on multivariable engine control is focused on the regulator problem of maintaining the engine near the desired operating trajectory. It is based on linear models valid for small signal analysis, and avoids the important problem of limit protection. The early 1974–1982 applications are summarized by Zeller, Lehtinen, and Merrill (11). The earliest work was that of McMorran and MacFarlane (12,13), which was tested on a two-spool afterburning engine. They used fuel flow to control compressor speed and A_8 to control fan speed due to the engine bypass duct.

The International Forum on Alternatives for Linear Multivariable Control (14), held in 1977, is of particular interest, because it showed the use of several multivariable techniques using a linear model of the F100 engine as a theme problem. Four authors developed control strategies based on three different multivariable techniques: multivariate transfer functions (15,16), Inverse Nyquist Array (17), and Characteristic Root Locus (18). Each strategy used three or four of the measured variables, fan speed, N_1, compressor speed, N_2, compressor exit speed, P_3, exhaust pressure, P_7, and turbine inlet temperature, FTIT and controlled fuel flow, W_f, exhaust nozzle areas, A_8, and compressor guide vanes, CIVV, or fan guide vanes, RCVV. In all cases, decoupled control of each of the measured variables was achieved.

One of the most complete early multivariable designs extensively tested was that by De Hoff and Hall (19–22) for the F100 engine, using extended linear quadratic regulator techniques. This work went beyond the previous studies, with ability to handle large power excursions without exceeding engine or actuator limits and to operate over the entire engine operating envelope. A block diagram of the control system is shown in Fig. 13. The feedback law itself is an optimal regulator structure, with integral trims for steady-state accuracy and engine limit tracking. Linear controllers were designed at five operating points: sea level static, subsonic and supersonic. Dominant gain elements were determined by assessing the closed-loop eigenvalue sensitivity to each gain element. Over 50 percent of the controller gains were eliminated in the final implementation, with little or no effect on system performance. Important gain elements were fitted with univariate functions of fan inlet pressure and temperature and core speed. Unique to this control design is the transition trajectory generator, whose purpose is to smooth rapid throttle changes by providing a piecewise linear transition from the current engine state to the requested state. The rate of transition depended on whether the engine is at low, medium, or high power.

Takeoff thrust for the F100 is defined as the thrust obtained at maximum allowable turbine temperature. At altitude conditions, the minimum burner pressure defines engine idle. Thus various physical limits must be held exactly at various flight conditions, as shown in Fig. 10. In theory, an optimal controller could have been designed for each limit at appropriate operating conditions. This would have required an exponentially large number of gain matrices to cover all combinations. De Hoff and Hall (19) used an ad hoc approach to solve this problem, by designing single-loop spectrally separated integral trims for each input, corresponding to each desired set point and number of unsaturated controls. The control was switched whenever an actuator saturated or an engine limit was reached.

A very similar multivariable design was developed for a GE23 variable cycle engine (23,24). A much larger number of linear design points were needed, due to the greater changes in engine configuration. Instead of using integral trim to handle engine limits, a model of the engine was incorporated into the transition logic. This allowed the generated trajectories always to satisfy engine limits. The problem with this approach is that it is an open-loop feedforward approach. How well the engine limits are held depends on the accuracy of the model and how well it can handle engine-to-engine variations.

One possible solution to handling engine limits is demonstrated by Adibhatla (25,26) for a short takeoff and vertical landing airplane (STOVL) using an F110 engine. This is a full-range multivariable design, which was pilot evaluated in the NASA Ames fixed-base and vertical-motion simulators. The primary objective of this engine control is to manage thrust, through the aft nozzle during cruise, and through ejectors at the aircraft wing roots and ventral ports on the underside of the aircraft during transition and hover. An estimate of thrust is determined based on fan speed, fan operating line, fuel flow, and the three thrust port areas. During cruise a 2×2 controller regulates fan speed and aft thrust, using fuel flow and aft nozzle area. During transition and hover, the controller is expanded to a 4×4 controller, in order to additionally regulate the ejector and ventral thrust using the ejector and ventral area actuators. To prevent engine stall and overtemperature, and to ensure sufficient pressure for customer bleed, three single-input, single-output regulators were designed as limit regulators.

Hanus' technique (27) for integrator antiwindup is used to transition between these five regulators and to handle actuator limits. In this technique, an "observer-based" structure is used, such that the normal controller is modified to assume the form:

$$\begin{aligned} \dot{x}_c &= A_c x_c + B_c(y_{sp} - y) + L(\text{sat}(u) - u) \\ u &= C_c x_c + D_c(y_{sp} - y) \end{aligned} \tag{15}$$

where A_c B_c C_c D_c the state space description of the five controller dynamics with the desired set point y_{sp} and the engine output y, sat(u) is the actual bounded engine input and L is the anti-windup gain. When a given regulator is controlling

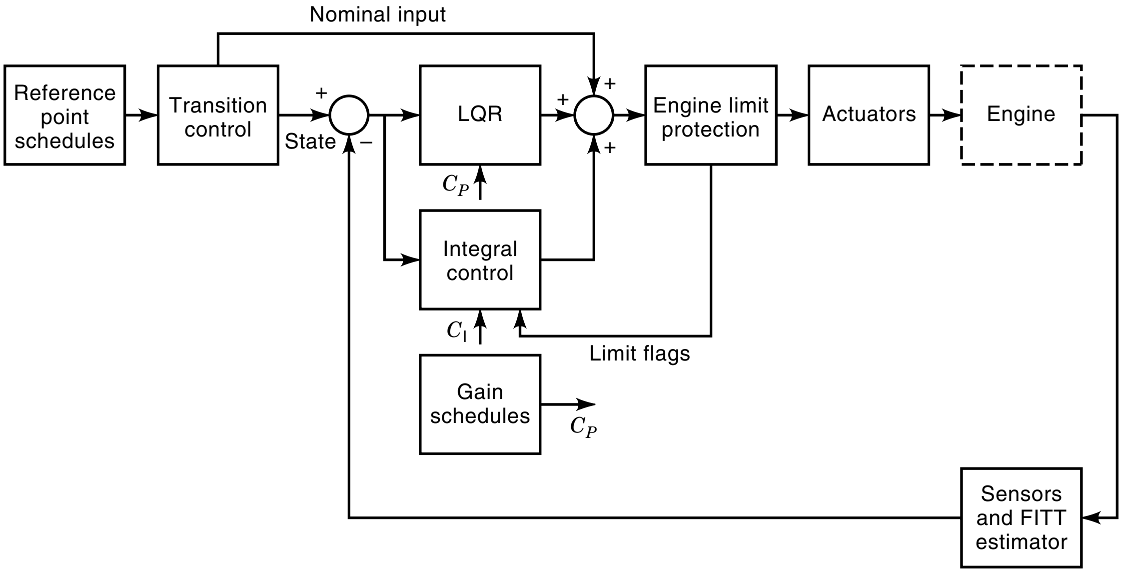

Figure 13. F100 multivariable controller (19).

the engine actuators, its elements of sat(u) − u are zero. The gain L forces the remaining sat(u) − u elements to zero, thereby tracking the ones currently applied to the engine. This ensures a smooth transition from one regulator to another, and automatically handles the problem of engine limits.

Recently, Kapoor and Teel (28) have extended Hanus' technique by replacing $L(\text{sat}(u) - u)$ with an equivalent dynamic system. This allows more design freedom and guarantees stability. An example is shown where their dynamic scheme gives response very close to the unconstrained case, while using a static L is unstable.

An excellent summary of multivariable control development in the United Kingdom from 1985 to 1995 is given by Dadd, Sutton, and Greig (29). A variety of control laws have been tested on either the RB199 or Sprey Mk202 engines. Each was distinguished primarily by the combination of sensor used, since there was very limited flexibility in terms of available actuators. Again the Hanus' technique (27) was used to handle limit protection and controller selection. Of specific interest is a "fast" response test on the Sprey Mk202 engine, using a 3 × 3 controller for most of the operating regime, and a 2 × 2 for low power settings where the high pressure inlet vanes are fully closed. The input output parameters chosen for the 3 × 3 controller were:

Inputs	**Outputs**
Fuel flow	Fan speed
Inlet guide vanes	Compressor speed
A_8 nozzle areas	Bypass duct Mach number

The 2 × 2 controller used fuel flow and nozzle area to control fan speed and bypass duct Mach number. Both the 2 × 2 and the 3 × 3 controllers were run simultaneously, with authority switched between them as the guide vanes either approached or moved off their limit.

During sea level static tests, it was found that this "fast response" multivariable controller produced a 60 percent reduction in time to go from 50 percent to 100 percent thrust. It was found that the specific fuel consumption was not affected significantly, while the thermal cycle range of the turbines was reduced. A second set of tests was performed, with increased integral gains to shift the closed-loop poles. This improved the robustness and disturbance rejection of the control.

CONCLUDING REMARKS

This article has focused on the basic theory of engine operation and on control designs currently in commercial and military use. Single-input, single-output controls are used on commercial engines where the emphasis in on economical operation. Multivariable controls provide enhanced performance for military engines. In both cases, the management of limits is an essential part of the control.

Due to limited space, it has not been possible to discuss the many ongoing advanced research areas in engine controls. Of immediate interest to the authors is the work (30,31) using a real-time model of the engine as an observer to provide estimates of unmeasurable variables, such as thrust and stall margins. Of much longer-term potential is the work on active control of stall (32–34) and combustion (35–37).

BIBLIOGRAPHY

1. G. G. Smith, *Gas Turbines and Jet Propulsion,* New York: Philosophical Library, 1955.
2. J. V. Casamassa and R. D. Bent, *Jet Aircraft Power Systems,* 3rd ed., New York: McGraw-Hill, 1965.
3. E. W. Constant II, The Origins of the Turbojet Revolution, Baltimore, MD: John Hopkins University Press, 1980.
4. I. E. Treager, *Aircraft Gas Turbine Engine Technology,* 2nd ed., New York: McGraw-Hill, 1979.
5. G. C. Oates, *Aerothermodynamics of Gas Turbine and Rocket Propulsion, Revised and Enlarged,* Washington, DC: American Institute of Aeronautics and Astronautics, 1988.

6. H. Cohen, G. F. C. Rogers, and H. I. H. Saravanamuttoo, *Gas Turbine Theory,* 4th ed., Essex U.K.: Longman, 1996.
7. Aerospace Recommended Practise, ARP 755A, Society of Automotive Engineers, 1974.
8. K. Mordoff, General Electric flies first unducted fan demonstrator, *Aviation Week & Space Technology,* **125**: 31, Aug. 25, 1986.
9. D. A. Parsons, N-dot schedules dynamic compensation system for gas turbines—Inputs sum of speed and rate of change of speed of gas generator to schedule to output desired acceleration as function of generator speed, U.S. Patent 5029441, 1991.
10. J. Zeller, B. Lehtinen, and W. Merrill, The Role of Modern Control Theory in the Design of Controls for Aircraft Turbine Engines, NASA Tech., Memo. 82815, Lewis Research Center, Cleveland, OH, 1982. (Also in AIAA Twentieth Aerospace Sciences Conf., Orlando, FL, Jan. 11–14, 1982.)
11. D. R. Gilmore, Jr., Two decades of T700 control system growth, *Proc. of the 4th CASI Symposium on Propulsion,* May 5, 1992, pp. 15–25.
12. P. D. McMorran, Design of gas-turbine controller using inverse Nyquist method, *Proc. of IEE* , **117**, 1970.
13. A. G. J. MacFarland et al., Application of multivariable control techniques to aircraft gas turbines, *Conf. on Multivariable Control Systems Design and Application,* Sept. 1–3, 1971.
14. M. K. Sain, J. L. Peczkowski, and J. L. Melsa, eds. *Alternatives for Linear Multivariable Control with Turbofan Engine Theme Problem,* Nat. Eng. Consortium, Chicago, 1978.
15. L. G. Hofmann, G. L. Teper, and R. F. Whitbeck, Application of Frequency Domain Multivariable Control Synthesis Techniques to an Illustrative Problem in Jet Engine Control, 51–70, in Reference 14.
16. J. L. Peczkowski and M. K. Sain, Linear multivariable synthesis with transfer functions, pp. 71–87, in Reference 14.
17. H. A. Spang, III, Insight into the application of the inverse Nyquist array method, pp. 138–155, in Reference 14.
18. B. Kouvaritakis and J. M. Edmunds, The characteristic frequency and characteristic gain design method for multivariable feedback systems, pp. 229–246, in Reference 14.
19. R. L. DeHoff et al., F100 Multivariable Control Synthesis Program, Vols. I and II, AFAPL-TR-77-35, June 1977.
20. C. J. Skira, R. L. DeHoff, and W. E. Hall, Jr., Design, Evaluation and Test of an Electronic, Multivariable Control for the F100 Turbofan Engine, AGARD-PP-274, Advanced Control System for Aircraft Power, Cologne, Germany, Oct. 1979.
21. R. L. DeHoff and W. E. Hall, Jr., Multivariable quadratic synthesis of an advanced turbofan engine controller, *J. of Guidance and Control,* **I**: 136–142, 1978.
22. R. L. DeHoff and W. E. Hall, Jr., Optimal control of turbine engines, *J. of Dynamic Systems, Measurements and Controls,* **101**: 117–126, 1979.
23. S. M. Rock and R. L. DeHoff, Variable Cycle Engine Multivariable Control Synthesis, AFAPL-TR-79-2043, 1979.
24. R. L. DeHoff and W. E. Hall, Jr., Multivariable control design principles applied to a variable cycle turbofan engine, *Proc. of the Asilomer Conf. on Circuits, Systems, and Computers,* Pacific Grove, CA, Nov. 1978.
25. S. Adibhatla, Propulsion Control Law Design for the NASA STOVL Controls Technology Program, AIAA, 93-4842, AIAA Int. Powered Lift Conf., Santa Clara, CA, 1993.
26. S. Adibhatla et al., STOVL Controls Technology, Vol. I, Integrated Flight/Propulson Control Design, NASA Contractor Report 195361, 1994.
27. R. Hanus, M. Kinnaert, and J. L. Henrotte, Conditioning technique, A general anti-windup and bumpless transfer method, *Automatica,* **23**: Nov. 1987.
28. N. Kapoor and A. Teel, A Dynamic Windup Compensation Scheme Applied to a Turbofan Engine, Proc. *36th IEEE Conf. on Decision and Control,* San Diego, CA, 4689–4694, 1997.
29. G. J. Dadd, A. E. Sutton, and A. W. M. Greig, Multivariable control of military engines, *Proc. Advanced Aero-Engine Concepts and Controls,* Defense Research Agency, Farnborough, England, June 1996. (AGARD Presentation, Seattle WA, Sept. 1995.)
30. W. J. Dwyer, Adaptive Model-Based Control Applied to a Turbofan Aircraft Engine, M.S. Thesis, Department of Mechanical Eng., MIT, Cambridge, MA, June 1990.
31. S. Adibhatla and T. Lewis, Model-Based Intelligent Digital Engine Control, AIAA 97-3192, *33rd AIAA Joint Propulsion Conf. & Exhibit,* Seattle, WA, July, 1997.
32. A. H. Epstein, J. E. Ffowcs-Williams, and E. M. Greitzer, Active suppression of aerodynamic instabilities in turbomachines, *J. Propulsion and Power,* **5** (2): 204–211, 1989.
33. I. J. Day, Active Suppression of Rotating Stall and Surge in Axial Compressors, International Gas Turbine and Aeroengine Congress and Exposition, ASME Paper 91-GT-87, June, 1991.
34. K. M. Eveker et al., Integrated control of rotating stall and surge in aeroengines, *Proc. Sensing, Actuation, and Control in Aeropropulsion Conf.,* Orlando, FL, Apr. 1995. (*SPIE Proceedings,* Vol. 2494, 1995, pp. 21–35.)
35. E. J. Gutmark et al., Active control in combustion systems with vortices, *Proc. 4th IEEE Conf. On Control Applications,* Albany, NY, Sept. 1995, pp. 679–684.
36. D. St. John and S. Samuelson, Optimal, active control of oxides of nitrogen (Nox) emissions from a natural gas-fired burner using a simple genetic algorithm., *Proc. 4th IEEE Conf. on Control Applications,* Albany, NY, Sept. 1995, pp. 673–678.
37. E. J. Gutmark et al., Compact waste incinerator based on vortex combustion, *Combustion Science and Tech.,* **121**: 333–349, 1996.

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