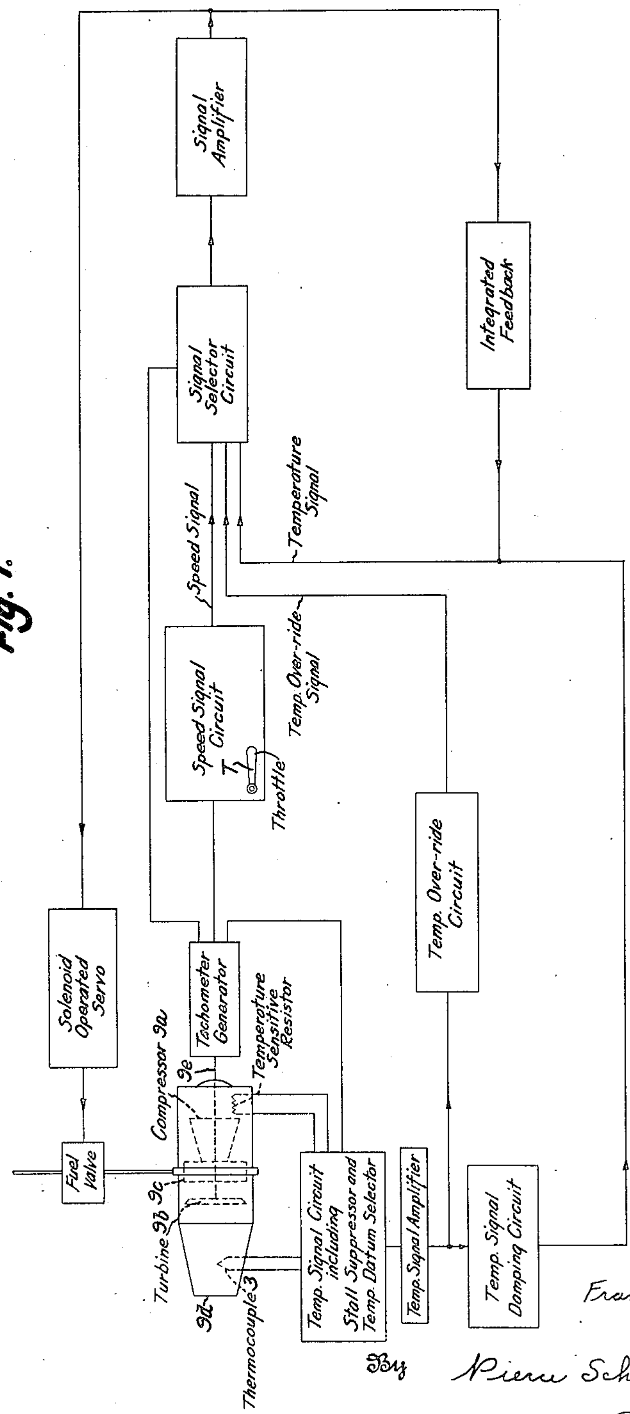
Dec. 28, 1954 F. F. OFFNER 2,697,908

SYSTEM FOR ACCELERATING ENGINES TO SELECTED SPEEDS AND MAINTAINING THE SPEED SELECTED

Filed March 31, 1949 4 Sheets-Sheet 1

Fig. 1.



Inventor

Franklin F. Offner

By Pierce Scheffler & Parker

Attorneys

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SYSTEM FOR ACCELERATING ENGINES TO SELECTED SPEEDS AND MAINTAINING THE SPEED SELECTED

Filed March 31, 1949 4 Sheets-Sheet 2

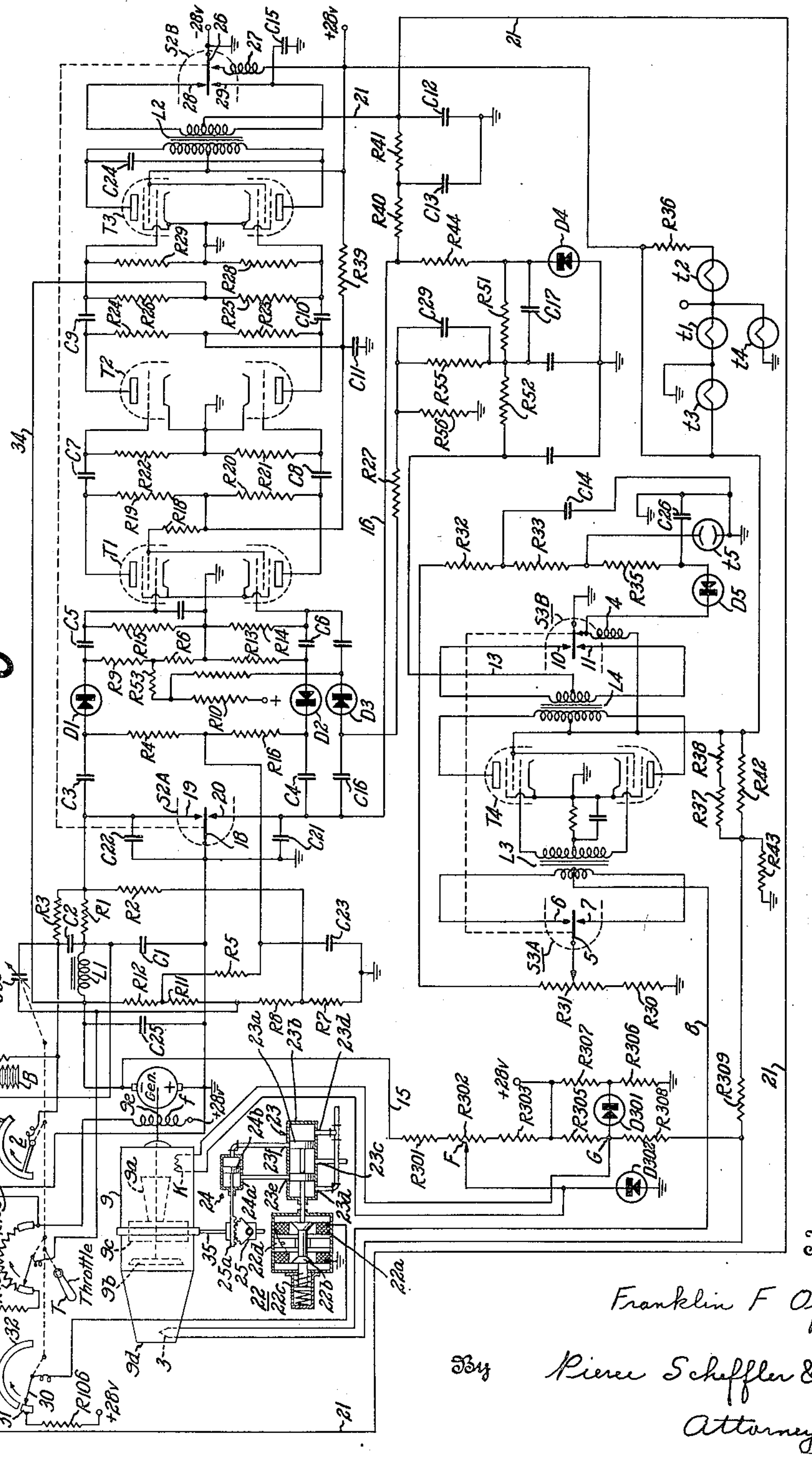


Fig. 2.

Inventor

Franklin F Offner

By Pierce Scheffler & Parker

Attorneys

Fig. 3.

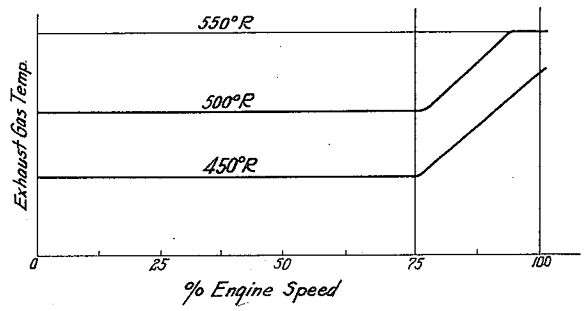
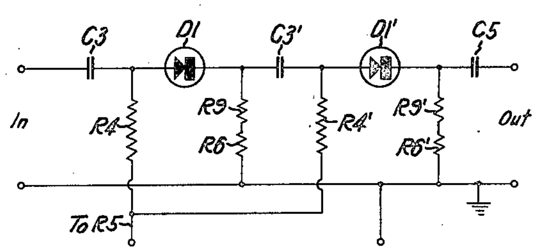


Fig. 4.



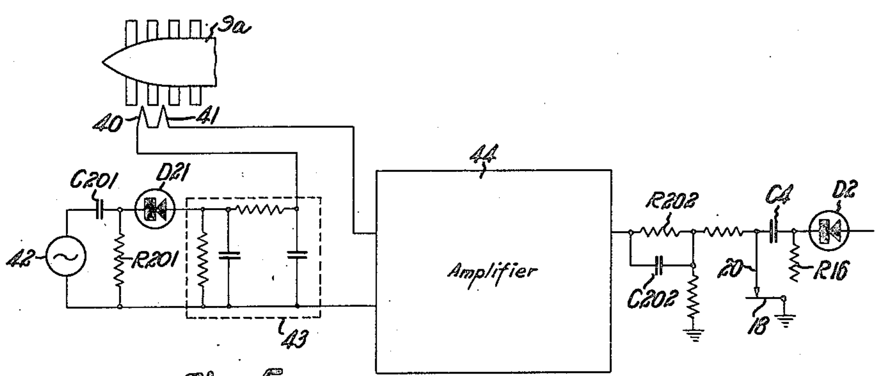


Fig. 5.

Inventor
Franklin F. Offner
By Pierce Scheffler & Parker
Attorneys

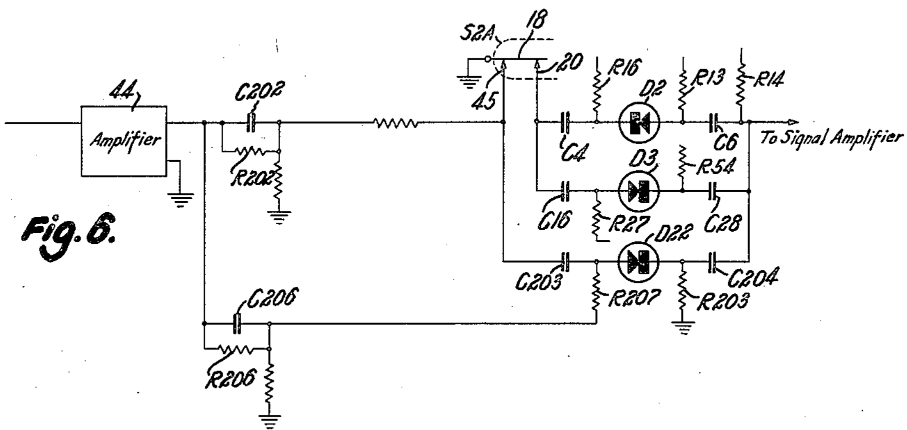


Fig. 6.

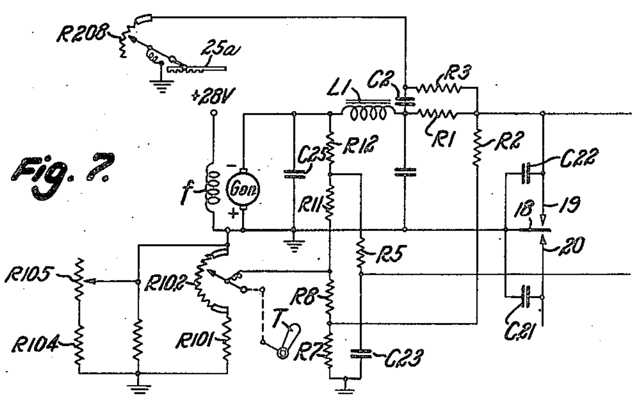


Fig. 7.

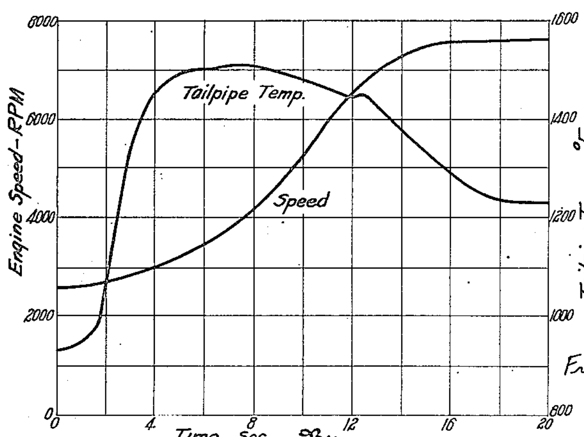


Fig. 8.

Inventor
Franklin F. Offner
By Pierce Scheffler & Parker
Attorneys

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2,697,908

SYSTEM FOR ACCELERATING ENGINES TO SELECTED SPEEDS AND MAINTAINING THE SPEED SELECTED

Franklin F. Offner, Chicago, Ill.

Application March 31, 1949, Serial No. 84,696

37 Claims. (Cl. 60—39.28)

This invention relates to control systems for engines as disclosed in my copending application Serial No. 770,872 filed August 27, 1947, now Patent No. 2,662,372, and in particular to an improved arrangement for controlling acceleration of an engine from an idling to a selected running speed in a manner consistent with maximum safe limits of engine parameters such as engine temperature and thereafter maintaining the engine at the selected running speed. While the invention is particularly well suited for use in scheduling fuel flow to an engine of the combustion gas turbine type widely known as a turbojet and it is with respect to such application that the invention is herein illustrated and described, it will be understood that some aspects of the inventive principles involved are applicable as well to other types of engines and the appended claims are to be construed accordingly.

An object of the invention is to provide a substantially all-electronic speed and acceleration control for turbo-jet engines that is extremely simple and reliable in operation, is relatively insensitive to large changes in ambient temperature or pressure and which will maintain the desired speed and acceleration within very close limits. Engine tests have shown that any selected engine speed is held automatically within one half per cent. Only one throttle or control lever is required and engine response to its movements is rapid but automatically held within the limits of safe engine operation.

Another object of the invention is to provide an adjsutable speed control for turbo-jet engines in which the fuel supply to the engine for acceleration purposes is generally scheduled as a function of engine temperature and any selected speed thereafter maintained as a function of instantaneous engine speed as compared with the selected speed.

Another object is to provide an electronic speed control for turbo-jet engines which permits the engine to be accelerated for any speed at a temperature close to but not exceeding a predetermined maximum allowable safe temperature in the tail pipe. With present turbo-jet engines, this maximum temperature limit is about 1,500° F. While it is not permissible to exceed the temperature limit neither is it desirable to accelerate at a lower temperature since this makes the engine acceleration time factor undesirably long. The latter factor is extremely important for Naval aircraft operating from carriers since a quickly responsive governor is mandatory under certain flight maneuvers such as a carrier wave-off. Assuming a plane coming in for a landing on the carrier deck with fully retarded throttle is, in the opinion of the landing officer flying at an altitude or speed unsafe for landing and the wave-off signal is given, it is essential that full engine power be available with the least possible time delay in the speed control system. The present system is admirably suited to such an eventuality and tests have shown that if the throttle lever is suddenly advanced after having been fully retarded and the engine is decelerating at its maximum rate, the fuel flow will increase to the maximum allowable value within one-half second after the throttle advance.

Another object is to provide a speed control for turbo-jet engine propelled aircraft that will hold the engine speed constant with altitude and varying load without "droop," the latter term being the proportionality between a change in load or fuel flow and off-speed.

Another object is to provide an adjustable electric speed

control of the null-seeking type for aircraft turbo-jet engines featuring derivative damping wherein future values of both speed and engine temperature are electronically determined by the preceding rates of change of these functions, and in which the amount of the damping is varied automatically with changes in altitude and/or speed of the aircraft.

Another object is to provide a speed control system for turbo-jet engines in which acceleration is in general controlled as a function of engine temperature, the temperature schedule of the control being automatically adjusted as a function of engine speed and/or air temperature at the compressor inlet to prevent stalling of the compressor blading which in turn leads to undesirable surging in the compressor.

Yet another object is to provide a speed control for turbo-jet engines in which acceleration of the engine is controlled as a function of the temperature rise through at least one stage of the compressor in order to prevent compressor surge.

Still another object is to provide a speed control for turbo-jet engines in which the temperature rise through the compressor or at least a portion thereof is limited so that it will not exceed a value that is allowed to increase as the square of the engine speed.

Another object is to provide a speed control of the null seeking type for rotating members wherein acceleration and speed of the member are controlled as a function of different parameters through a cross-over circuit that automatically selects the respective parameter signals, the cross-over circuit being comprised of cascaded unidirectional conducting devices in order to more effectively block out the non-selected signal from the control.

The foregoing as well as other objects and advantages of the invention will become more apparent from the following detailed description and accompanying drawings for a preferred construction in which

Fig. 1 is a circuit diagram in block schematic of the improved electronic speed control;

Fig. 2 is a more detailed diagram showing circuit details of the principal components in Fig. 1;

Fig. 3 is a series of curves pertaining to a detail of the control;

Fig. 4 is a sub-circuit diagram illustrating a modified form of cross-over circuit components featuring cascaded rectifiers to improve their blocking action relative to incoming signals;

Fig. 5 is also a sub-circuit diagram showing a modified arrangement for the Fig. 2 control wherein acceleration of the engine is scheduled as a function of temperature rise across a stage of the compressor and also engine speed to prevent the compressor from stalling;

Fig. 6 is likewise a sub-circuit diagram illustrating alternative use of the circuit shown in Fig. 5 only for protection against compression surge in the engine leaving the main control functions on a basis of tail pipe temperature as shown in Fig. 2;

Figure 7 is also a sub-circuit diagram illustrating a modification for a portion of the Fig. 2 circuit and which features scheduling of the derivative damping component of the speed signal in accordance with fuel flow; and

Fig. 8 depicts plots of engine temperature and speed respectively against time illustrating a typical engine response.

Referring now to the drawings and particularly Figs. 1 and 2 for the present, the turbo-jet engine **9** is of typical design being comprised of a multi-stage axial flow compressor **9*a*** driven by a single stage axial flow turbine **9*b*** with a series of combustion chambers **9*c*** therebetween, and a tail pipe **9*d*** through which the turbine exhaust gases are discharged rearwardly to effect forward propulsion of the engine.

Engine speed is sensed by a special tachometer generator GEN driven off the engine shaft **9*e*** which puts out a direct current voltage proportional to speed. This voltage is compared with a reference voltage set by the throttle T in a bridge. The difference voltage and a derivative term derived from the generator voltage are combined to constitute the speed signal. Similarly, a temperature sensing element (in the present case a parallel connected thermocouple group 3 in the tail pipe of the engine) is used to develop a voltage variable with tail pipe temperature, and this voltage combined with its derivative term constitute the temperature signal. The speed and temperature signals are both fed into an electronic selector which blocks one or the other of them dependent upon the engine speed. At engine speeds below a predetermined percentage of a particular speed selected which can be called the cross-over point, only the temperature signal is passed by the selector and at speeds higher than this only the speed signal is passed. The signal passed by the selector is then amplified and applied to a proportional solenoid 22 that controls the fuel valve 25 on the engine through a hydraulic servo 23, 24.

Speed circuit

The speed signal which exercises control over the speed of the engine after the cross-over point has been reached is obtained from a bridge circuit which includes the output from the tachometer direct current generator GEN driven by the engine, a speed selector potentiometer R102 adjusted by throttle T, and resistors R1 and R2. A large voltage is desired for the cross-over network in the selector circuit that is later described while a much smaller reference voltage is desired for the speed signal bridge. Consequently, in the latter, the output of the potentiometer is divided by resistors R7, R8 to give the desired lower reference voltage for the speed circuit. The bridge output is taken from the junction point of R1 and R2. The tachometer generator is so designed that the armature voltage is very closely proportional to speed and field current. The generator field winding *f* is connected in series with the speed selector potentiometer R102 to the positive terminal of a 28 v. source of direct current. Thus, if it be assumed that the engine speed is such that the bridge circuit is balanced and the bridge output therefore zero, then any fluctuation in the 28 v. supply will change the current through the generator field winding *f* and also through the speed setting potentiometer R102. But this change in field current will produce an exactly proportional change in the output voltage of the generator and hence the bridge will remain balanced. It will be evident that for the same reasons, any variation in the resistance value of field winding *f*, or temperature will not affect the speed setting. Furthermore, the generator resistance is so low as compared to resistor R1 that changes in generator armature resistance will also be ineffective in causing speed changes.

As previously explained, the bridge functions to continuously compare the tachometer generator voltage with the speed reference voltage set by potentiometer R102 and puts out a speed signal component proportional to the difference between the two voltages and the polarity of which (positive or negative) depends upon the direction of the bridge unbalance. In the present arrangement, if the generator voltage is below that set on potentiometer R102, the speed signal component will be positive; if above, then the signal will have a negative polarity.

To improve the sensitivity-response characteristic of the control system, I prefer to combine with the speed signal component described in the preceding paragraph a derivative term which algebraically adds to such component another signal component that varies with the rate-of-change of the tachometer voltage. This is often referred to as derivative anticipation and makes it possible to stabilize the control system without the use of "droop." A satisfactory approximation of the speed derivative term is obtained through resistor-condenser circuit combinations. Since the amount of derivative term required for critical damping is a function of both altitude and speed, I prefer to vary the same automatically as the aircraft engine changes speed and/or altitude, by means of a rotary switch 2 ganged to the throttle lever T controlling the position of the speed selector potentiometer R102 which alters the capacitance of the condenser component as a function of speed and a variable resistor R60 controlled by an atmospheric pressure responsive bellows B for altering the resistance component as a function of altitude.

At sea level, the position of the bellows B will be such that the resistor has a minimum in-circuit value and the derivative term is established by a circuit to which the tachometer generator voltage is applied, the circuit including condenser C2 and resistor R3 connected in series and altitude variable resistor R60 shunting the same, the effect of the resistor R60 being to reduce the time constant of the resistor R3 condenser C2 combination and the derivative voltage that would be produced by the same. As the voltage setting on speed reference potentiometer R102 is reduced, i. e. toward reduced speed, additional differentiating condensers C101, C102 are successively added in circuit with condenser C2 thus lengthening the differentiated time constant and increasing the derivative term. The speeds at which condensers C101, C102 come in, as well as their capacitance value are so chosen that satisfactory damping is obtained at all speeds.

As the altitude is increased from sea level, the altitude responsive bellows B progressively increases the in-circuit value of the shunting resistor R60. This further increases the derivative term and lengthens the differentiation time constant so that satisfactory damping will be maintained at all altitudes. These step like changes in the differentiation time constant as distinguished from a uniformly variable type of control has been found satisfactory since the amount of damping required is not too critical. Thus the use of variable condenser values as speed is changed and variable shunting resistance with changes in altitude gives a derivative damping term which is the product of the two factors, and correct damping will be maintained over the full speed range as the altitude varies.

Any minor and slow fluctuations in the potential applied to the reference +28 volt terminal and which is usually obtained from batteries will have no adverse effect upon operation of the control system. However, in the event that the battery voltage should shift rapidly, the response of the speed generator circuit to transients is different from the response of the reference voltage source. This is so because the reference voltage is applied purely through resistive paths while the speed generator voltage is applied both through a resistor and the damping condenser C2. Thus the circuit while balanced for slow changes in the battery voltage, is not balanced for rapid changes. This defect is overcome by the use of variable condenser C60 connected between the output lead from the speed selector potentiometer R102 and one side of condenser C2, and which serves to make the time constant of both paths identical.

Condenser C60 also has another function. When small changes are made on the speed adjusting potentiometer R102, the normal action of the damping circuit without condenser C60 would be to delay the speed response of the engine according to the time constant of the damping circuit. Addition of condenser C60, however, cancels out the time constant of the damping circuit by the compensating time constant of the speed control circuit. Then, for small changes in potentiometer R102, very rapid response of the control system is assured. During large changes in potentiometer R102, the main amplifier for the signals saturates, and therefore the additional condenser C60 has little effect. This prevents the circuit from giving sudden excessively large increments of fuel which might result in over-temperature occurring so suddenly that the protective temperature over ride circuit, to be explained later, could not prevent damage to the engine.

To eliminate the derivative compensating effect it is best to vary the capacitance of condenser C60 with changes in the setting of potentiometer R102 to maintain transient balance and this can easily be done by switching in successive values of this condenser with the control for potentiometer R102 as indicated diagrammatically on the drawing.

The derivative term of the speed voltage combines electrically with the speed term voltage at the bridge output, and the combined speed voltage signal is applied to the selector circuit that is to be subsequently described. Resistors R107, R108 connected respectively between differentiating condensers C101, C102 and the positive, grounded terminal of the tachometer generator are provided for the purpose of maintaining the voltage across these condensers at its equilibrium value, and eliminate switching transients.

Associated with the speed signal circuit just described, is a filter for eliminating fluctuations in the signal. These fluctuations may be of two types: Normal fluctuations due to commutator ripple in the tachometer generator, as well as torsional engine oscillations; and abnormal fluctuations which may result from either a dirty generator commutator, or due to the brushes vibrating off the commutator periodically. The first type of fluctuation is characterized by relatively constant input impedance, and by not affecting the average value of the speed voltage. Its effect is reduced to a negligible amount by the half section of the filter consisting of inductance **L1** and condenser **C1** in the output circuit of the generator. This filter serves to greatly attenuate rapid fluctuations in voltage, and eliminates the alternating current component, leaving the direct current component unchanged. The second type of fluctuation is minimized by the input condenser **C25** connected across the output circuit of the generator which functions in the following manner: When the generator brushes are properly in contact with the commutator, condenser **C25** will be charged fully to the speed voltage of the generator. As the generator resistance in the present control circuit is approximately 50 ohms, and condenser **C25** has a capacitance of one microfarad, it will be charged with a time constant of 50 microseconds—that is, almost instantly. Assume then that one brush leaves the generator commutator. Then the generator impedance is at that instant infinite. Condenser **C25** must accordingly discharge through the filter and resistor **R1**. The effective time constant of this circuit will be of the order of one second. Thus the voltage will change only inappreciably during the brief fraction of a second that the brush may have left the commutator.

It is possible that transients of such speed may occur in the +28 volt power supply battery that the time constant of filter **L1**, **C1** may be sufficient to disturb the transient balance. To avoid this effect, the filter may be moved if necessary to the output side of the derivative damping circuit for the speed voltage signal: that is, it may follow the junction point of **R1**, **R2** and **R3**.

Temperature control circuit

The control system according to the invention makes use of a temperature control circuit for controlling acceleration of the engine up to a predetermined percentage of the engine speed selected on the throttle **T**. This control is related to the instantaneous temperature of the engine as measured at the tailpipe so that the desired tailpipe temperature is maintained during acceleration.

In particular, the temperature circuit begins at a temperature sensing unit, preferably a thermocouple **3** located in the tailpipe of the engine, the function of which is to produce a control quantity dependent upon tailpipe temperature. In this case, the control quantity is a voltage generated by the thermocouple and such voltage is bucked against an adjustable datum voltage obtained from the voltage drop across adjustable resistor **R31** and fixed resistor **R30**. The datum voltage is obtained from a source that derives its voltage from the inductive kick of the operating coil **4** of the vibrating switch **S3B**, the inductive surge being rectified by rectifier **D5** and filtered. The convention observed with respect to the illustration of rectifier **D5** as well as the other rectifiers used in the entire control system is that electron flow is in the direction of the arrow. The filtered voltage is then dropped to a neon voltage regulating tube **T5** through resistor **R35**. The output voltage from tube **T5** is further filtered and reduced by dropping it through resistors **R32** in conjunction with condenser **C14**, and then applied to resistors **R30** and **R31**.

The difference between the selected datum voltage and the output voltage of the thermocouple **3** is taken in a circuit constituted by a vibrating switch **S3A** comprising a vibratory contact reed **5** that takes on the datum voltage via a connection to the adjustable contact on resistor **R31** and which works between a pair of stationary contacts **6**—**7** connected respectively to the ends of the primary of transformer **L3**. The thermocouple voltage is applied via conductor **8** to a center tap on the primary of transformer **L3**. Thus the difference between the datum and thermocouple voltages which will be positive when the thermocouple voltage is below the datum voltage and negative when above, is applied in succession to each half of the primary of transformer **L3** as the vibrating contact **5** engages first one and then the other of the stationary contacts **6**, **7**.

The corresponding outputs from both halves of the center tapped secondary of transformer **L3** are amplified respectively in a double tube **T4** and the plate circuits of the latter applied to the end terminals of the primary of output transformer **L4**. The secondary of the latter has its end terminals connected to the stationary contacts **10**, **11** of vibratory switch **S3B** previously mentioned and the amplified output constituting the instantaneous difference between the datum and thermocouple voltages is taken off through lead **13** connected to a center tap on the secondary of output transformer **L4**.

The vibrating switches **S3A** and **S3B** are ganged together for synchronous operation, such being indicated schematically on the drawing by the broken line interconnecting the vibrating reed contacts of the two switches, and hence serve to provide the desired chopping of the difference voltage at the input side of the amplifier tubes **T4** and the synchronous unchopping of the amplified voltage at the output side of the amplifier so that the amplification is essentially an alternating current operation. The chopper type amplifier is considered preferable to other known means for amplifying direct current signal voltages for various reasons and some of its advantages are discussed hereinafter in connection with the description of the main amplifier for the temperature and speed signals.

It will be noted from the circuit diagram that the other side of thermocouple **3** is connected to a bridge network of resistors **R42**, **R43**, **R37** and **R38**. This serves two functions. Resistor **R37** has a negative temperature coefficient. This is adjusted so that it gives "cold junction compensation" according to well known principles. Specifically, it causes the voltage at the ungrounded end of resistor **R43** to rise **40** micro-volts for every degree centigrade rise in the temperature of resistor **R37**, thus giving the same net voltage from the thermocouple **3** with changes in ambient temperature.

The second function of the bridge network will be apparent from the following: Voltage regulator tube **T5** does not give perfect regulation. Should the voltage applied to this tube rise about 10% for example, the voltage at the output of tube **T5** would be found to have risen about 1%. To compensate out any such error, the resistance bridge is adjusted so that the voltage at the ungrounded end of resistor **43** is, at normal ambients, 10% of the voltage taken from adjustable resistor **R31** (at normal temperature datum). Then the voltage changes at resistor **R31**, and at the ungrounded end of resistor **R43**, with changes in input voltage to tube **T5** will be substantially equal and thus cancel out.

Stall suppressor circuit

In the operation of jet engines, particularly at high altitudes, conditions are encountered where the compressor may surge due to stalling of the compressor blading. I have discovered that such surges may be effectively prevented by controlling the temperature either at the turbine inlet or in the turbine discharge, i. e. in the tailpipe. This is so because I have discovered that compressor stall is uniquely determined by inlet temperature, speed, and either turbine inlet or tailpipe temperature. The temperature must be scheduled as a function of the temperature of the air at the inlet to the compressor. Because the surging tendency is also a function of engine speed, the temperature schedule must also be modified according to the speed of the engine.

In Fig. 3, I have shown a series of typical curves with maximum allowable tailpipe temperature plotted against engine speed for several different temperatures of air at the compressor inlet.

At an air inlet temperature of 550° Rankine, it will be observed that the maximum allowable tail pipe gas temperature curve runs parallel with the abscissa which is to say that at all engine speeds, the allowable exhaust gas temperature is limited only by the temperature limitation of the engine, and maximum exhaust gas temperature consistent with safety limits of the engine may be employed.

At 500° Rankine, it will be observed that a lower exhaust gas temperature must be maintained up to the 75% of maximum speed mark if compressor stalling is to be prevented, but that above such speed, higher exhaust gas temperature is allowable until finally when the 90% speed mark is reached the allowable engine temperature is no longer limited by the compressor surge factor but again by the physical temperature limitations of the engine itself. Thus from the 90% speed mark to maximum (100%) engine speed, the 500° curve coincides with the 550° curve.

At 450° Rankine, still lower exhaust gas temperatures must be observed if stalling in the compressor is to be prevented. Examination of the 450° curve will show that while increasing temperatures are allowable at engine speeds above the 75% speed mark, the maximum allowable at maximum engine speed is well below the maximum temperature limitation of the engine as represented by the 550° curve.

The required scheduling of temperature to prevent surging in the compressor is accomplished by superimposing an additional control factor upon the temperature circuit since the output signal from thte temperature sensing unit used primarily for controlling acceleration of the engine can easily be modified to incorporate this additional scheduling factor.

Referring again to the circuit diagram shown in Fig. 2, the stall suppression section appears at the lower left corner. When for example the engine is at maximum speed, the negative output terminal of the tachometer generator will be at its most negative value with respect to ground (the positive terminal being grounded). Resistors **R301** and **R303**, connected in circuit with the negative generator terminal via lead **15**, are in such ratio as determined by the adjustable tap on **R302** that tap point F is now negative, so that no current flows through rectifier **D302**.

Assume now that the temperature at the inlet to the compressor unit **9***a* of the jet engine **9** is high i. e. of the order of 550° R. This temperature is sensed by a resistor unit K placed there, and which has a highly negative temperature coefficient of resistivity. The resistance of the temperature sensing resistor K will then be relatively low. Under these conditions point G at the junction of resistors **R305**, **R308** would have essentially the same voltage as point F, and therefore would also be negative. Rectifier **D301** is, however, so polarized that point G can never become negative, but only goes down to zero potential. Thus no modifying voltage will be added to that produced by the tail pipe thermocouple **3** via resistor **R308** connected in circuit with the latter as seen from the input side of the amplifier unit for the temperature signal. The net result is that tailpipe temperature is scheduled in accordance with the maximum limits of the engine itself as set on the temperature datum selector (potentiometer **R31**).

As the engine speed decreases, point F will eventually become positive at which time rectifier **D302** starts to conduct so that point F remains at zero potential. Since the compressor inlet temperature sensing resistor K is at a low resistance value because of the assumed high inlet temperature, point G also has essentially zero potential, and no voltage signal is applied to the tailpipe temperature input circuit via resistor **R308** at any engine speed. Thus the scheduled temperature would follow the 550° curve in Fig. 3.

At a lower compressor inlet temperature for example 500° R., the temperature sensing resistor K will of course have a higher resistance due to its negative temperature coefficient. Thus when the engine speed is low, and point F is at essentially zero potential, temperature sensing resistor K and resistor **R305** form a voltage divider from the +28 volt terminal to zero, giving a proportionate fraction of positive voltage at point G. This positive voltage is applied to resistor **R308**, and flowing through resistor **R309** adds a potential in series with that produced by the temperature sensing thermocouple **3** in the tailpipe, which results in an overall lowered exhaust gas temperature in the tailpipe. This temperature will then remain unchanged up to the point where point F becomes negative at the 75% speed mark on the Fig. 3 curve. Above this speed, the voltage at point G is lowered by the more negative voltage at point F. This results in a continually lower voltage being applied to resistor **R308** as the speed increases so that the exhaust gas temperature is lowered by a lesser amount. As the speed continues to increase, point G eventually starts to become appreciably negative, the voltage in series with that produced by the thermocouple would reverse; i. e. the two voltages would oppose each other, so that higher than maximum allowable temperatures as set on potentiometer **R31** would be called for. However, rectifier **D301** prevents point G from becoming negative, so that at the 90% speed mark in Fig. 3, the temperature has reached its maximum value, and at higher speeds the tailpipe temperature follows the maximum 550° R. curve up to maximum engine speed.

At even lower compressor inlet temperatures, the effect is the same as outlined in the preceding paragraph, with the inlet temperature sensing resistor K having continually higher resistances as the inlet temperature decreases. However, at sufficient low temperatures, the voltage at point G will not have become negative by the time that maximum engine speed is reached, so that even at the 100% speed mark, the exhaust gas temperature in the tailpipe will not have reached its maximum level but will be at a lesser value.

It will be evident that by varying the magnitude of the various resistors in the stall suppressor circuit, and the resistance-temperature characteristic of the temperature sensing resistor K it is possible to modify the temperature scheduling curves of Fig. 3 to match the characteristics of the particular engine type under consideration.

The purpose of the resistors **R306** and **R307** is to provide a small positive bias on rectifier **D301**. This increases the rapidity with which the rectifier flattens out the curve at the maximum temperature limit. It both decreases the effect of rectifier resistance, and the minimum resistance of temperature sensing resistor K.

Temperature stabilizing circuit

In order to obtain stable control over the temperature signal as modified by the stall suppressor circuit, two stabilizing circuits are employed at the output of the temperature signal circuit. The first of these is constituted by condenser **C17** and resistor **R51** connected in parallel by which the temperature signal voltage is partially differentiated. The second of the two stabilizing circuits is constituted by resistor **R41** and condenser **C13** connected to the output from the main amplifier, to be subsequently discussed, that establishes an integrated feedback signal. The latter is coupled out through resistor **R40** and combined with the differentiated temperature signal coupled out through resistor **R44**. The combined output signal is then introduced into the electronic selector circuit also to be discussed below over conductor **16**.

The function of rectifier **D4** connected between ground and one side of condenser **C17** is to limit the maximum output of the temperature circuit. The electronic circuit is limited in voltage handling capacity by the available cross-over bias. Rectifier **D4** serves to limit the temperature output signal to a value that will not overload the circuit and starts to conduct at a potential just about sufficient to give full amplifier output. Thus it does not limit performance of the temperature regulating circuit.

The theory of the temperature regulating circuit is probably rather involved. Briefly, however, it is believed to function in the following manner. The time constant of the differentiating circuit (resistor **R51** and condenser **C17**) is approximately equal to the time constant of the temperature sensing thermocouple **3**. It can be shown that under such conditions, the effective time constant of the over-all circuit is not a function of either time constant individually but rather a shorter time period determined by the electrical circuit components. In the present circuit, the effective value is only about ⅕ the temperature unit time constant, or an almost negligible short value. It can be shown that, in the linear range of the amplifier, the integrated feed-back circuit (resistor **R41**—condenser **C13**) is equivalent derivative anticipation. It thus serves to stabilize the temperature signal circuit in the same manner as the derivative damping circuit in the speed signal circuit, and the component values may be chosen to provide critical damping.

Selector circuit

As mentioned in the introduction, the present electronic control system functions as a regulator for the tailpipe temperature of the engine during periods of acceleration; and as an all-speed governor when in the vicinity of the selected speed desired to be maintained. The selection of function is automatically made in the electronic selector circuit now to be described.

The direct current speed signal and the temperature signal are both chopped by an electrically maintained vibrating reed switch **S2A** containing a contact reed **18** electromagnetically vibrated between two stationary contacts **19, 20**. The contact reed is connected to ground and thus as it vibrates the direct current speed and temperature signal voltages will be alternately and periodically grounded thus giving them an essentially alternating current characteristic. The two signals are introduced respectively into selenium rectifiers **D1, D2** that are oppositely polarized with respect to the incoming signals, and a variable bias voltage is applied to each of the rectifiers through the coupling resistors **R4, R16**. The bias voltage is obtained from a "cross-over" bridge consisting of the tachometer generator voltage, the voltage of speed control potentiometer **R102**, and two resistors **R11, R12** so chosen that the bridge is balanced at approximately 80% of the engine speed selected on potentiometer **R102**. It will be seen that at engine speeds lower than this, the output of the cross-over bridge will be positive, so that current will flow through rectifier **D2** while rectifier **D1** will be cut off. Current flowing through the rectifier indicates that its impedance in the direction of current flow is fairly low and thus it will also transmit the essentially alternating current temperature signal. On the other hand, since rectifier **D1** is cut off, it will transmit neither a direct current, nor the essentially alternating current speed signal. In a similar manner, above the "cross-over" speed, the polarity of the bridge output will reverse, becoming negative, so that now rectifier **D1** will become conducting whereas rectifier **D2** will now be cut off, the effect of which is to transmit the essentially alternating current speed signal through rectifier **D1** and block out the temperature signal at rectifier **D2**. Thus the selection of signal is made automatic in accordance with engine speed.

Rectifiers D1, D2 do not cut off infinitely sharply, nor exactly at zero voltage. The cut-off point is adjusted so that the two overlap slightly by inserting a small positive voltage in series with resistor **R9**, this voltage being obtained from a suitable source through resistor **R10**.

Main amplifier

As previously mentioned, the signals as initially developed by both the speed circuit and temperature circuit are direct current. The use of such a signal is desirable since it allows differentiation, integration and other forms of computation to be employed as necessary. However, the usual form of direct current amplifier is entirely unsuitable for control use. Types of direct current amplifiers previously considered have included straight D. C. electronic amplifiers, ring modulators, and galvanometer amplifiers. The latter have taken the form of either photoelectric pick-up, or a form of inductive pick-up. All these forms of amplifier suffer from a common difficulty; the balance point is not stable, and must be adjusted from time to time, thus making them unsuited for control applications.

The amplifier about to be described has none of these drawbacks and is admirably suited to the speed control system. As mentioned in the previous section dealing with the selector circuit, the direct current speed and temperature signals are first interrupted by the vibrating switch **S2A** thus converting them into essentially alternating current signals which can then be amplified by a conventional alternating current amplifier. The amplifier consists of three stages **T1, T2** and **T3** and is arranged push-pull throughout. The first stage **T1** is a double pentode amplifier and acts as a phase inverter for signals introduced into either grid, the speed signal being applied through coupling condenser **C5** to the grid of the upper half of the tube and the temperature signal through coupling condenser **C6** to the grid of the lower half of the tube. The last stage **T3** is a power amplifier, and it is transformer coupled to the output vibrating switch **S2B** and to the load which is constituted by a proportional solenoid **22** that controls the pilot valve **23** of a hydraulic servo **24** which in turn controls the supply of fuel to the jet engine **9** through valve **25**.

Switch S2B like switch S2A includes a contact reed **26** electromagnetically vibrated by interrupter coil **27** between two stationary contacts **28, 29**. The contact reeds of the two switches S2A, S2*b* are arranged to operate synchronously, both being preferably ganged and driven from the same vibrator coil as indicated diagrammatically on the circuit diagram, and hence switch **S2B** will rectify the amplifier output, giving again a direct current output signal, proportional in amplitude and in this case reversed in sense to the input signal, but greatly amplified which signal is applied from a mid tap on the secondary of output transformer **L2** to the fuel valve operating solenoid **22**.

Because of the 180° relative phase reversal of the signal resulting from the use of opposed contacts of S2A for chopping the speed and temperature signals, the signals are applied to opposite grids of the push-pull input. Thus a negative (over-speed) speed signal and a negative (over-temperature) signal at S2A each operate to reduce fuel flow.

It will be noted that in the circuit connections **21** from the amplifier output to the proportional solenoid **22**, a control switch **S101A** is inserted. This switch includes a contact arm **30** electrically connected to the operating coil 22*a* of solenoid **22** and mechanically ganged to the control throttle T, and which wipes over an arcuate track providing alternative circuit connections to the solenoid coil. The track is sectionalized providing a narrow contact segment **31** with which the contact arm **30** is engaged when the throttle T occupies its closed position, and a wide contact segment **32** engaged by the arm **30** after throttle T has been moved to any desired open position. Contact segment **32** is connected to the signal output lead **21** from transformer L2 to thus apply the speed and temperature control signals to the solenoid coils **22*a***. Contact segment **31** is, however, connected through resistor **R106** to the positive terminal of the 28 volt supply line so that when the throttle is closed, positive voltage is put on the solenoid coils to thus close the fuel valve completely.

A few special features of the amplifier are well worth noting. The amplifier operates from 28 volts plate supply with no inverter, etc. This low value of supply voltage requires some special design in the amplifier. However, as exact maintenance of input wave form is not necessary, the problem is simplified. Use of high values of grid resistor, with grid current bias, stabilizes tube characteristics. In the output stage, improved performance is possible with some negative bias on the grids. Cathode bias could be used but this would reduce the already low available plate supply. The only source of negative voltage is the tachometer generator. The grid bias used on the output stage is not critical, and the generator voltage is of approximately the proper magnitude. Accordingly, the grid resistors **R25, R26** of the output stage are returned via conducted **34** to the negative tachometer generator terminal.

To eliminate undesired voltage fluctuations of the +28 volt plate supply line, an RC filter consisting of resistor **R39** and condenser **C11** filters the plate supply to the first two stages of the amplifier. Condensers **C15** and **C24** are used to improve the wave form of the transmitted signal. Condenser **C12** is required to absorb the inductive surge from the load of the proportional solenoid **22** during the switching transients of the vibrating reed switch **S2B**.

The amplifier circuit has proved to be unusually reliable. This probably is due both to the use of the low plate supply voltage which produces a minimum of strain on the tubes, and to the uncritical nature of the amplifier. Rather wide variations in tube characteristics can be tolerated, without appreciably affecting control performance. In addition, failure of one section of either of the two latter stages will only reduce the amplifier sensitivity and output, but will not cause a complete failure.

Proportional solenoid

The proportional solenoid **22** includes an armature **22*b*** biased to a neutral position by springs **22*c*** that operates the piston member **23*a*** of pilot valve **23**. Cylinder **23*b*** of the valve contains a central high pressure fluid inlet **23*c***, low pressure outlets **23*d*** at each end lead to a sump, and high pressure fluid outlets **23*e*, 23*f*** leading to the opposite ends of the cylinder **24*a*** of servomotor **24**. The piston **24*b*** of the servomotor actuates fuel valve **25** in the fuel injection line **35** leading to the jet engine **9** to control the rate of fuel flow to the combustion chambers.

The proportional solenoid **22** also includes an annular permanent magnet **22*d*** for setting up a magnetic field which when combined with the magnetic field produced electromagnetically by the signal current in coils **22*a*** produces axial movement of armature **22*b*** in one direction or the other from its neutral position fixed by the loading springs **22*c*** dependent upon the sense of the current flow through these coils which in turn depends upon the polarity of the rectified output signal at output transformer L2 of the signal amplifier.

The corresponding motion imparted to valve piston **23***a* places the high pressure inlet **23***c* in communication with one end of cylinder **24***a* of servomotor **24** and the other end of cylinder **24***a* in communication with one of the low pressure outlet lines **23***d* causing servomotor piston **24***b* to shift axially and change the setting of the fuel valve **25**. Movement of solenoid armature **22***b* in the opposite direction from its neutral position in response to an output control signal of opposite polarity will of course have an opposite effect on the setting of the fuel valve **25**.

Temperature over-ride

Under normal conditions, when it is desired to accelerate from an idling to some selected running speed, the tailpipe temperature will be comparatively low and hence the temperature signal at S2A at the beginning will be strongly positive. This positive signal (after chopping) is then put through the selector circuit and amplifier and effects an opening of the fuel valve causing the engine to accelerate rapidly with an attendant rise in tail pipe temperature. Should the latter, however, rise above the datum level set on the datum temperature selector potentiometer R31 during the period before the cross-over speed is reached, the temperature signal will swing negative, the effect of which is to cause the fuel valve **25** to move toward a more closed position.

After the cross-over speed has been reached at which instant the selector circuit cuts off the temperature signal and cuts in the speed signal, any rise in tailpipe temperature above the selected acceleration datum value is automatically detected by a temperature over-ride circuit and the fuel rate reduced until the temperature recedes to the selected maximum. This reduction in fuel rate thus limits the acceleration rate at speeds above the cross-over speed when the derivative damping circuit would otherwise call for too high an acceleration rate. The over-ride protective circuit also comes into operation when the control is on speed governing whenever the tailpipe temperature exceeds the acceleration datum value. It also comes into operation should any abnormal condition arise such as the clogging of one or more nozzles so that excessive temperatures would be required to maintain the speed setting on the throttle.

The temperature over-ride circuit consists of a rectifier D3 transmitting a signal effectively in parallel with the normal temperature signal transmitter rectifier D2. However, while rectifier D2 obtains its bias through resistor R16 from the signal selector (cross-over) circuit, the bias for the over-ride rectifier D3 is supplied from the output of the thermocouple amplifier through a differentiating network consisting of resistors R55, R56 and C29. This network operates in a manner similar to the differentiating network previously described for stabilizing the temperature signal and serves to partially cancel the time delay inherent in the response characteristic of the thermocouple **3**. The bias voltage existing at the ungrounded end of resistor R56 is applied to rectifier D3 through resistor R27. Through the time constant cancelling action of the network, the bias applied to rectifier D3 becomes negative at the same instant as the temperature signal applied to the rectifier D2 from the other differentiating network, through resistor R44. Thus rectifier D3 starts to conduct at the instant the temperature signal indicates that the temperature of the exhaust gases is above the allowable datum level. Were it not for the differentiating network R55, R56, C29, the signal would not be transmitted until the actual temperature of the thermocouple had reached the datum level which because of the inherent time delay constant of the thermocouple may not occur until several seconds after the exhaust gas has reached the selected datum level. Rectifier D3 accordingly will pass the output of the temperature circuit into the main amplifier at any speed above the cross-over speed whenever the exhaust gas temperature is above the temperature datum set on potentiometer R31 notwithstanding the fact that at such time rectifier D2 is cut off.

Operation

While the operating principles of the control system have already been discussed in part in connection with the description of its component parts, a review here of the entire sequence of events which take place when the pilot of the jet propelled plane wishes to accelerate the jet engine, with reference to the speed and temperature curves shown in Fig. 8 that are typical of the results produced, will be conducive to a complete understanding of the invention.

Referring now to Fig. 8, with the engine **9** running at an idling speed of 2700 R. P. M., the output of the cross-over bridge in the selector circuit will be negative and hence the speed of the engine is regulated in accordance with the output signal of the speed circuit applied through rectifier switch D1 and the main amplifier to the control winding **22***a* of the proportional solenoid **22**. The speed signal will of course be zero if the engine speed agrees with the selected speed setting on potentiometer R102; if the two are in disagreement, a signal of the proper polarity to supply the necessary correction to the fuel valve **25** will be generated in the speed circuit and put through the amplifier to the fuel control solenoid **22**.

With the engine running at 2700 R. P. M., the temperature in the tailpipe will normally be quite low as compared to the selected maximum level set on the temperature datum potentiometer R31. Thus, for example, if a datum level of 1500° F. is selected, the tailpipe temperature may be of the order of 930° F.

Now assume that the pilot desires to increase the engine speed up to a running speed of about 7800 R. P. M. The throttle T is pushed forward and the corresponding change in the potential taken off potentiometer R102 immediately swings the output of the crossover bridge from negative to positive thus cutting off the speed signal transmission at rectifier D1 and putting the rectifier D2 into condition for passing control signals from the temperature circuit.

With the tail pipe temperature down about 570° F. below the selected datum level, the initial signal output from the temperature circuit amplifier will be strongly positive and therefore result in an initially high rate of increase of fuel through valve **25** with an attendant steep rise in the tail pipe temperature and the latter soon approaches the datum level thus lowering the temperature signal. However, as the engine continues to pick up speed, the resulting increase in the exhaust gas velocity tends to cool off the tail-pipe somewhat so that the temperature signal is maintained. That is to say, the tail pipe temperature will normally remain below the selected datum level and the fuel rate will continue to increase although at a reduced rate.

When the engine speed reaches the point where the output of the cross-over bridge in the selector circuit swings back to a negative value, signal transmission through the switching rectifier D2 associated with the temperature signal circuit becomes blocked and rectifier D1 unblocks so that the signal produced by the speed circuit is then put through to the solenoid **22** and controls the remainder of the engine acceleration until the selected speed is reached. As the engine speed approaches the selected speed, the speed signal gradually decreases to zero and the speed circuit thereafter continues to exercise control over the engine speed to maintain the latter substantially constant.

The tail pipe temperature lowers with increased engine speed and will stabilize well below the datum level after a fairly high speed is reached. In the curves of Fig. 8, it will be observed that the tail pipe temperature stabilized at about 1300° F. when the selected speed of 7800 R. P. M. was reached.

Modified stall suppressor circuit

An alternative method of scheduling acceleration of the engine to prevent compressor stall is shown in the sub-circuit diagram of Fig. 5 and its operation is predicated upon the following relations. I have discovered that the temperature rise across a given stage of the compressor (assuming an axial flow construction for example) at the stall line varies as the square of the engine speed. That is, if at a speed of 1,000 R. P. M., a compressor stage stalls at a certain pressure ratio across the compressor, the temperature rise in the air passing through that stage may be, for example, ten degrees centigrade. Then if the engine is rotating at a speed of 2,000 R. P. M., if the pressure rise across the compressor is again increased sufficiently to make this stage stall, the temperature rise will be four times the previous value, or forty degrees centigrade. The temperature rise across several stages of the compressor may also be employed for the above purpose. In general, compressor surge occurs due to stalling of the same rows of blades initially in various operating regimes of the engine.

With reference now to Fig. 5, it will be observed that two heat sensing elements such as the thermocouples **40** and **41** are placed on each side of one of the blade rows in the compressor *9a*. These thermocouples are connected in series opposition so their net voltage output will vary with the difference in temperature across the blade row. A small alternating current generator **42** driven by the engine in the same manner as the main direct current tachometer generator GEN is used, and the output voltage of the generator **42** will increase as a linear function of speed as will also the frequency. Therefore the differentiated output voltage of the generator will increase as the square of the engine speed. The output of generator **42** is preferably differentiated by a network consisting of condenser **C201** and resistor **R201** but any of the other well known differentiating circuits may be employed as well, such as for example a transformer with a low inductance primary.

The derivative voltage across resistor **R201** is rectified by rectifier **D21** and applied to filter **43**. The output voltage from the filter is in such sense as to buck the voltage of the thermocouples **40, 41**. The net output of this circuit is then applied to an amplifier **44** of the vibrating type such as that used in the circuit shown in Fig. 2 for initially amplifying the output of the thermocouple in the tailpipe. For simplicity in illustration, the amplifier has accordingly been shown in block schematic only. The output of the latter is then fed through a condenser-resistor compensating network **C202, R202** similar to the compensating network (resistor **R51** and condenser **C17**) used at the output of the amplifier for the tail pipe thermocouple voltage and which functions in like manner to reduce the effect of the temperature lag inherent in the thermocouples.

The output from the compensating network **C202, R202** can be used in the circuit shown in Fig. 2 in place of the output from the compensating network associated with the amplified voltage signal from the tail pipe thermocouple by connecting it to condenser **C4** and opening the output from the tailpipe thermocouple compensating network at resistor **R44**. In this way acceleration of the engine will be scheduled not in accordance with tail pipe temperature but rather along the surge line of the compressor *9a* up to the cross-over speed at which the selector circuit cuts out this signal and cuts in the signal from the speed circuit. A safe margin must be allowed in the scheduling to prevent marginal surge from occurring.

When the surge scheduling circuit of Fig. 5 is employed, protection against over temperature can be obtained by using the same over-ride circuit (resistors **R27, R56, R55** and condenser **C29**) as is used when acceleration is scheduled in accordance with temperature in the tailpipe, except that in such case the stall suppressor circuit associated with thermocouple **3** in the tailpipe would be eliminated.

Alternatively, engine acceleration may be scheduled as a function of tailpipe temperature in the manner according to the Fig. 2 circuit and the circuit shown in Fig. 5 used only for protection against surge. With this arrangement, the main control attempts to main the temperature called for by the tail pipe thermocouple **3** during acceleration, but in the event that the surge line of the compressor is approached, the Fig. 5 circuit will reduce fuel to prevent surge. One method by which this can be accomplished is shown in Fig. 6. Here the output of the compressor temperature amplifier **44** is applied to a lag compensating network **R202, C202** and thence after chopping by an additional stationary contact **45** on vibrator switch **S2A** to the input of the main amplifier through condenser **C203**, rectifier **D22** and the necessary coupling resistor **R203** and condenser **C204**. The required bias for rectifier **D22** is supplied in a manner similar to that shown for the tailpipe temperature over-ride control, through a condenser-resistor compensating network **C206, R206** in conjunction with resistor **R207**.

Modified damping circuit for speed signal

The control circuit shown in Fig. 2 uses condensers **C101, C102** and variable resistor **R60** for altering the derivative term of the speed signal as a function of speed and altitude. If desired, the modified arrangement shown in the sub-circuit diagram of Fig. 7 may be employed. Condensers **C101, C102** are eliminated as is also the altitude responsive resistor **R60**, and a variable resistor **R208** coupled to the fuel valve control rod *25a* is substituted. The variable resistor **R208** is connected in shunt to the derivative network for the speed signal comprising condenser **C2** and resistor **R3**, and is arranged in such manner that it has a minimum in-circuit resistance when the fuel valve is wide open, and hence brings the derivative damping term of the speed signal to its minimum value. As the fuel valve is moved towards a more closed position, the in-circuit resistance value of resistor **R208** is increased, thus increasing the derivative term and hence also the damping action.

Since lower speed requires lower fuel flow; and also high altitude at a constant speed requires low fuel flow, and in each instance, more damping is required, it is seen that an increase of damping as a function of fuel flow always operates in the correct direction to give the desired damping. Furthermore, it can be shown that the amount of damping required at a given fuel flow is approximately the same, whether the decrease in fuel flow be a result of increased altitude or decreased speed.

Modified selector circuit

It will be recalled from the previous section dealing with the selector circuit that the respective signals from the temperature and speed circuits are selectively put through to the main amplifier and hence to the fuel control in accordance with the ratio between the instant engine speed and the speed selected on potentiometer **R102**. If this ratio is below a predetermined amount, for example .8, the selector blocks the speed signal and passes the temperature signal; when the ratio passes .8, the selector then blocks the temperature signal and passes the speed signal. The selection is effected through the instrumentality of rectifier type switches connected respectively between the speed and temperature signal outputs and the amplifier input to which a biasing voltage is applied, the polarity of which reverses from positive to negative when the above mentioned ratio passes the selected changeover point. If the potential at the junction point of condenser **C3** and biasing resistor **R4** is negative with respect to the potential at the junction of resistor **R9** and condenser **C5** which condition prevails when the ratio is above the predetermined fraction of the selected speed, only rectifier **D1** will conduct. Accordingly, this rectifier will transmit the alternating component of the speed signal to the amplifier input, while rectifier **D2** will effectively block transmission of the temperature signal because the same negative biasing voltage makes the potential at the junction of condenser **C4** and biasing resistor **R16** negative with respect to the potential at the junction of condenser **C6** and resistor **R13**, and rectifier **D2** it will be remembered is oppositely poled from rectifier **D1**. Thus under such condition rectifier **D2** will exhibit a high impedance to current transmission through it. When the ratio is below the preselected fraction, the biasing voltage becomes positive thus setting up the converse condition, i. e. rectifier **D2** will then pass the alternating component of the temperature signal and rectifier **D1** will block off transmission of the speed signal because of the high impedance it exhibits under such condition. Normally the rectifier impedance will be high enough to enable it to perform its switching function satisfactorily. However, unlike a more positively acting switch, a rectifier of the dry type such as a copper oxide or selenium unit cannot offer infinite impedance and should there be any leakage through the same irrespective of the amplitude of the blocking potential applied, which is the equivalent of shunting the rectifier by a high resistance, the rectifier cannot help but pass some of the signal at the input side. If the latter is sufficiently high it can of course cause defective operation of the circuit.

The alternative arrangement for each of the switching rectifiers as shown in Fig. 4 will serve to greatly inhibit any undesired leakage through the rectifiers. The circuit is similar to that illustrated in Fig. 2 but features two such rectifiers connected in cascade for each signal. The arrangement for the speed signal only has been illustrated, but it will be understood that a similar circuit is provided for the temperature signal. The first section is identical with that of Fig. 2 with the cross-over voltage being applied over resistor R4 and the speed signal over condenser C3 to rectifier D1. When the cross-over voltage is negative, rectifier D1 will exhibit a low impedance to flow of current and hence the latter will contain a pronounced component corresponding to the speed signal. However, instead of applying the output of rectifier D1 directly to the input of the main amplifier, it is applied to the condenser component C3' of another rectifier circuit containing rectifier D1', resistor R4' connected in parallel with resistor R4, and resistors R9', R6' corresponding to and of like circuit arrangement as resistors R9 and R6. Assuming the cross-over voltage to be still negative, the second rectifier D1' likewise exhibits a low impedance and hence passes the speed signal. On the other hand, when the cross-over biasing voltage swings positive, the total attenuation factor of the rectifiers becomes equal not to the sum of each but to their product. Thus assuming rectifiers D1 and D2 each show an attenuation factor of thirty, the overall attenuation would not be sixty but rather nine hundred which will provide a very satisfactory control response with a large margin of safety since any leakage will then become inconsequential.

In conclusion, I wish it to be understood that while the invention has been described with reference to particular embodiments, various changes may be made therein by those skilled in the art without departing from the spirit and scope of the invention as defined in the appended claims. For example, while the tachometer generator coupled to the engine for providing a control voltage proportional to speed is shown as a direct current machine, one of the alternating current type provided with rectifiers in its output circuit will operate equally as well.

I claim:

1. In a device for controlling acceleration and speed of an engine the combination comprising; means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible engine temperature, means producing a voltage variable with engine temperature and circuit means comparing said voltages and from which is produced a first control voltage variable as the difference between said compared voltages; a throttle member, means controlled by said throttle member for establishing a reference voltage variable with the throttle setting, means driven by said engine for generating a speed voltage variable with engine speed and circuit means comparing said voltages and which produces a second control voltage variable as the difference between said compared voltages; electro-responsive means controlling fuel flow to said engine; and means selectively applying said first and second control voltages to said electro-responsive means to control respectively the acceleration of said engine and the selected running speed thereof as determined by said throttle setting.

2. In a device for controlling acceleration and speed of an engine the combination comprising; means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible engine temperature, means producing a voltage variable with engine temperature and circuit means comparing said voltages and from which is produced a first control voltage variable as the difference between said compared voltages; a throttle member, means controlled by said throttle member for establishing a reference voltage variable with the throttle setting, means driven by said engine for generating a speed voltage variable with engine speed and circuit means comparing said voltages and which produces a second control voltage variable as the difference between said compared voltages; means for producing a cross-over voltage variable with engine speed; means responsive to said control voltages for controlling fuel admission to said engine; and first and second switching means individual respectively to said first and second control voltages and actuated alternatively in accordance with the amplitude of said cross-over voltage for alternatively transmitting said control voltages to said fuel control means.

3. An engine control device as defined in claim 2 and which further includes a third switching means connected in parallel with said first switching means, actuation of said third switching means being controlled in accordance with said first control voltage for transmitting the latter to said fuel control means.

4. In a device for controlling acceleration and speed of an engine the combination comprising; means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible engine temperature, means producing a voltage variable with engine temperature and circuit means comparing said voltages and from which is produced a first control voltage the amplitude and sense of which are determined by the amplitude and sense of the difference between said compared voltages; a throttle member; means controlled by said throttle member for producing a reference voltage variable with the throttle setting, means for generating a speed voltage variable with engine speed, and circuit means comparing said voltages and which produces a second control voltage the amplitude and sense of which are determined by the amplitude and sense of the difference between said compared voltages; means for producing a cross-over voltage variable with engine speed; means responsive to said control voltages for controlling fuel admission to said engine; and first and second switching means individual respectively to said first and second control voltages and actuated alternatively in accordance with the amplitude of said cross-over voltage for alternatively transmitting said control voltages to said fuel control means.

5. An engine control device as defined in claim 4 and which further includes a third switching means connected in parallel with said first switching means, actuation of said third switching means being controlled in accordance with the sense of said first control voltage for transmitting the latter to said fuel control means irrespective of the amplitude of said cross-over voltage.

6. In a device for controlling speed and acceleration of a combustion gas turbine engine of the type including coupled turbine and multistage compressor units and a combustion chamber unit therebetween, the combination comprising; means producing a signal voltage variable as the temperature rise across at least one stage of said compressor unit, means producing a second voltage variable as the square of engine speed, and circuit means comparing said voltages to produce a first control voltage the amplitude and sense of which are determined respectively by the amplitude and sense of the difference between said compared voltages; a throttle member; means producing a reference voltage the amplitude of which is varied in accordance with the throttle setting, means producing a speed voltage variable as a linear function of the engine speed, and circuit means comparing said reference and speed voltages and which produces a second control voltage the amplitude and sense of which are determined by the amplitude and sense of the difference between said compared voltages; means for producing a cross-over voltage variable with engine speed; means responsive to said first and second control voltages for controlling fuel admission to said combustion chamber unit, and first and second switching means individual respectively to said first and second control voltages and actuated alternatively in accordance with the amplitude of said cross-over voltage for alternatively transmitting said control voltages to said fuel control means.

7. In a device for controlling speed and acceleration of a combustion gas turbine engine of the type including coupled turbine and multi-stage compressor units and a combustion chamber unit therebetween, the combination comprising; means producing a signal voltage variable with the temperature of the combustion gases, means establishing a constant reference voltage the amplitude of which is representative of a selected maximum permissible combustion gas temperature, and circuit means comparing said voltages and from which is produced a first control voltage whose amplitude and sense are determined by the amplitude and sense of the difference between said compared voltages; a throttle member; means controlled by said throttle member for producing a second reference voltage variable with the throttle setting, means producing a voltage variable linearly with engine speed, and circuit means comparing said voltages and from which is produced a second control voltage whose amplitude and sense are determined by the amplitude and sense of the difference between said compared voltages; means producing a signal voltage variable as the temperature rise across at least one stage of said compressor unit, means producing another signal voltage variable as

the square of engine speed and circuit means comparing said voltages to produce a third control voltage whose amplitude and sense are determined by the amplitude and sense of the difference between said compared voltages; means producing a cross-over voltage variable with engine speed; means responsive to and circuit connected with said control voltages for controlling fuel admission to said combustion chamber unit; and first, second and third switching means individual respectively to said first, second and third control voltages and arranged in the respective circuit connections to said fuel control means, said first and second switching means being controlled by said cross-over voltage and actuated alternatively in accordance with the amplitude thereof to alternatively transmit said first or second control voltage to said fuel control means, and said third switching means being controlled by said third control signal and actuated in accordance with the sense thereof to transmit the same to said fuel control means.

8. In a device for controlling speed and acceleration of a combustion gas turbine engine of the type including coupled turbine and multistage compressor units and a combustion chamber unit therebetween, the combination comprising; means producing a signal voltage variable as the temperature rise across at least one stage of said compressor unit, means producing a second voltage variable as the square of engine speed, and circuit means comparing said voltages to produce a first control voltage the amplitude and sense of which are determined respectively by the amplitude and sense of the difference between said compared voltages; a throttle member; means producing a reference voltage the amplitude of which is varied in accordance with the throttle setting, means producing a speed voltage variable as a linear function of the engine speed, and circuit means comparing said reference and speed voltages and which produces a second control voltage the amplitude and sense of which are determined by the amplitude and sense of the difference between said compared voltages; means producing a signal voltage variable with the temperature of the combustion gases, means establishing a constant reference voltage the amplitude of which is representative of a selected maximum permissible combustion gas temperature, and circuit means comparing said voltages and from which is produced a third control voltage whose amplitude and sense are determined by the amplitude and sense of the difference between said compared voltages; means for producing a cross-over voltage variable with engine speed; means responsive to and circuit connected with said control voltages for controlling fuel admission to said combustion chamber unit; and first, second and third switching means individual respectively to said first, second and third control voltages and arranged in the respective circuit connections to said fuel control means, said first and second switching means being controlled by said cross-over voltage and actuated alternatively in accordance with the amplitude thereof to alternatively transmit said first or second control voltage to said fuel control means, and said third switching means being controlled by said third control signal and actuated in accordance with the sense thereof to transmit the same to said fuel control means.

9. In a device for controlling acceleration of an engine from idling speed, means producing a signal voltage variable with engine temperature, means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible engine temperature, circuit means comparing said voltages and from which is produced a control voltage output variable as the difference between said compared voltages, means responsive to said control voltage output for scheduling fuel admission to said engine in accordance with the amplitude of said output, means responsive to engine speed for rendering said control voltage ineffective when a predetermined engine speed has been reached, and speed dependent means effective at engine speeds above said predetermined speed to schedule fuel admission to said engine.

10. In a device for controlling acceleration from idling speed of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber unit therebetween, the combination comprising, means producing a signal voltage variable with the temperature of the combustion gases, means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible combustion gas temperature, circuit means comparing said voltages and which produces a control voltage variable as their difference, means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage, means responsive to engine speed for rendering said control voltage ineffective when a predetermined engine speed has been reached, and speed dependent means effective at engine speeds above said predetermined speed to schedule fuel admission to said engine.

11. In a device for controlling acceleration of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber therebetween, the combination comprising, means producing a signal voltage variable with the temperature of the combustion gases, signal modifying means including a temperature sensing device responsive to air temperature at the air inlet to said compressor unit for effecting an apparent increase in said signal voltage upon a decrease in compressor air inlet temperature, means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible combustion gas temperature, circuit means comparing said voltages and which produces a control voltage variable as their difference, and means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

12. An engine control device as defined in claim 11 in which said signal modifying means also includes means responsive to engine speed for likewise effecting an apparent increase in said voltage signal upon a decrease in speed.

13. In a device for controlling acceleration of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber unit therebetween, the combination comprising, means producing a first signal voltage variable with the temperature of the combustion gases, means including a temperature sensing device responsive to air temperature at the air inlet to said compressor unit for producing a second signal voltage variable inversely as the change in air temperature at said compressor inlet, means establishing a constant reference voltage the magnitude of which is representative of a selected maximum permissible combustion gas temperature, circuit means comparing said voltages and which produces a control voltage variable as the difference between said reference voltage and the sum of said first and second signal voltages, and means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

14. In a device for controlling acceleration of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber unit therebetween, the combination comprising, means producing a first signal voltage variable with the temperature of the combustion gases, means including a temperature sensing device responsive to air temperature at the air inlet to said compressor unit and a device responsive to engine speed for producing a second signal voltage variable inversely as the change in engine speed and also inversely as the change in air temperature of said compressor inlet, means establishing a constant reference voltage the amplitude of which is representative of a selected maximum permissible combustion gas temperature, circuit means comparing said voltages and which produces a control voltage variable as the difference between said reference voltage and the sum of said first and second signal voltages, and means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

15. In a device for controlling acceleration of a combustion gas turbine engine of the type including coupled turbine and multi-stage compressor units and a combustion chamber therebetween, the combination comprising, means producing a signal voltage variable as the temperature rise across at least one stage of said compressor unit, means responsive to engine speed for producing a second signal voltage variable as the square of engine speed, circuit means comparing said voltages to produce a control voltage variable as their difference, and means

responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

16. In a device for controlling acceleration of a combustion gas turbine engine of the type including coupled turbine and multi-stage compressor units and a combustion chamber unit therebetween, the combination comprising, means producing a first signal voltage variable as the temperature rise across at least one stage of said compressor unit, an alternating current signal generator driven by said engine and which produces a voltage whose amplitude and frequency both vary as a linear function of engine speed, circuit means differentiating the output voltage of said generator to produce a second signal voltage which therefore varies as the square of engine speed, circuit means comparing said first and second signal voltages to produce a control voltage variable as their difference, and means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

17. In a device for controlling the speed of an aircraft propelled by a combustion gas turbine engine of the type including coupled turbine and compressor units, and a combustion chamber therebetween; a throttle member, means controlled by said throttle member for producing a reference voltage variable with the throttle setting, means generating a speed voltage variable as a linear function of engine speed, a differentiating circuit having an adjustable time constant connected to said voltage generating means for producing a derivative voltage term variable as the rate-of-change of said speed voltage, means controlled by said throttle member for shortening the time constant of said differentiating circuit as said throttle member is moved to a more open position and vice versa, circuit means comparing said voltages and which produces a control voltage variable as the difference between said reference voltage and the sum of said speed voltage and its derivative term, and means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

18. In a device for controlling the speed of an aircraft propelled by a combustion gas turbine engine of the type including coupled turbine and compressor units, a combustion chamber therebetween and a fuel valve controlling admission of fuel to said chamber; a throttle member, means controlled by said throttle member for producing a reference voltage variable with the throttle setting, means generating a speed voltage variable as a linear function of engine speed, a differentiating circuit having an adjustable time constant connected to said voltage generating means for producing a derivative voltage term variable as the rate-of-change of said speed voltage, means controlled by said fuel valve for shortening the time constant of said differentiating circuit as said fuel valve is moved to a more open position and vice versa, circuit means comparing said voltages and which produces a control voltage variable as the difference between said reference voltage and the sum of said speed voltage and its derivative term, and means responsive to said control voltage for actuating said fuel valve in accordance with the amplitude of said control voltage.

19. In a device for controlling the speed of an aircraft propelled by a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber unit therebetween, a throttle member, means controlled by said throttle member for producing a reference voltage variable with the throttle setting, means generating a speed voltage variable as a linear function of engine speed, a differentiating circuit having an adjustable time constant connected to said voltage generating means for producing a derivative voltage term variable as the rate-of-change of said speed voltage, means controlled by said throttle member for shortening the time constant of said differentiating circuit as said throttle member is moved to a more open position and vice versa, means responsive to atmospheric pressure for lengthening said time constant as said pressure decreases with an increase in altitude of said aircraft and vice versa, circuit means comparing said voltages and which produces a control voltage variable as the difference between said reference voltage and the sum of said speed voltage and its derivative term, and means responsive to said control voltage for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

20. In a device for controlling the speed of an aircraft propelled by a combustion gas turbine engine of the type including coupled turbine and compressor units, a combustion chamber unit therebetween and an electro-responsive valve controlling admission of fuel to said combustion chamber; a throttle member, means controlled by said throttle member for producing a reference voltage variable with the throttle setting, means generating a speed voltage variable as a linear function of engine speed, a resistor-condenser type differentiating circuit connected to said voltage generating means for producing a derivative voltage term variable as the rate-of-change of said speed voltage, means controlled by said fuel valve for adjusting the ohmic value of a resistor component of said differentiating circuit in such sense as will shorten the derivative term when said fuel valve is moved to a more open position and vice versa, circuit means comparing said voltages and which produces a control voltage variable as the difference between said reference voltage and the sum of said signal voltage and its derivative term, and circuit means applying said control voltage to the electro-responsive member of said valve for scheduling fuel admission to said combustion chamber unit in accordance with the amplitude of said control voltage.

21. A device for controlling acceleration and speed of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber therebetween, said device comprising means producing a first control signal variable with the difference between the actual combustion gas temperature of said engine as compared with a predetermined maximum permissible temperature, means producing a second control signal variable with the difference between the actual speed of said engine as compared with a selected running speed desired to be maintained, means actuated by said control signals for scheduling admission of fuel to said combustion chamber, and means responsive to the speed of said engine for applying only said first control signal to said fuel scheduling means at engine speeds below a predetermined fraction of said selected running speed and similarly applying only said second control signal at engine speeds above said predetermined fraction.

22. A control device as defined in claim 21 and which further includes means modifying said first control signal as a function of air temperature at the air inlet to the compressor unit of said engine.

23. A device for controlling acceleration and speed of a combustion gas turbine engine of the type including coupled turbine and multi-stage compressor units and a combustion chamber therebetween, said device comprising means producing a first signal variable with the temperature rise across at least one stage in the compressor unit, means producing a second signal variable as the square of actual engine speed, means comparing said first and second signals to produce a first control signal variable with the difference therebetween, means producing a second control signal variable with the difference between the actual speed of said engine as compared with a predetermined running speed desired to be maintained, means actuated by said control signals for scheduling admission of fuel to said combustion chamber, and means responsive to engine speed for applying only said first control signal to said fuel scheduling means at engine speeds below a predetermined fraction of said selected running speed and similarly applying only said second control signal at engine speeds above said predetermined fraction.

24. A device for controlling acceleration of a combustion gas turbine engine of the type including coupled turbine and multi-stage compressor units and a combustion chamber therebetween, said device comprising means producing a first signal variable with the temperature rise across at least one stage in the compressor unit, means producing a second signal variable as the square of actual engine speed, means comparing said signals to produce a control signal variable with the difference therebetween, and means actuated by said control signal for scheduling admission of fuel to said combustion chamber.

25. A device for controlling the speed of an aircraft propelled by a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber therebetween, said device comprising means producing a first signal proportional to actual

engine speed, means obtaining a derivative term from said first signal determined jointly by a selected engine speed desired to be maintained, the rate-of-change of engine speed and the altitude of the aircraft, means combining said first signal and the said derivative term thereof to produce a combined signal, means producing a second signal representative of said selected engine speed, means producing a control signal variable as the difference between said combined signal and said second signal, and means actuated by said control signal for scheduling admission of fuel to said combustion chamber.

26. A device for controlling the speed of an aircraft propelled by a combustion gas turbine engine of the type including coupled turbine and compressor units, a combustion chamber therebetween and a fuel valve controlling admission of fuel to said combustion chamber, said device comprising means producing a first signal proportional to actual engine speed, means obtaining a derivative term from said first signal determined jointly by the position of said fuel valve and the rate-of-change of engine speed, means combining said first signal and the said derivative term thereof to produce a combined signal, means producing a second signal representative of a selected engine running speed desired to be maintained, means producing a control signal variable as the difference between said combined signal and said second signal, and means applying said control signal to said fuel valve for actuating the same.

27. In a device for controlling an engine, the combination comprising means producing a temperature signal variable with engine temperature, means producing a speed signal variable with engine speed, means connected with and actuatable by one or the other of said signals for scheduling fuel admission to said engine, signal switching means interposed in the connections between said signals and said fuel scheduling means, and control means responsive to engine speed and operable at a fraction of a selected steady state engine speed for actuating said signal switching means to cut in one of said signals and simultaneously cut out the other signal, said control means effecting connection of only said temperature signal through said switching means to said fuel scheduling means at engine speeds below the operating point of said control means, and said control means effecting connection of only said speed signal through said switching means to said fuel scheduling means at engine speeds above the operating point of said control means.

28. A device for controlling acceleration and speed of an engine comprising means producing a first control signal variable with the difference between the actual temperature of said engine as compared with a predetermined maximum permissible temperature, means producing a second control signal variable with the difference between the actual speed of said engine as compared with a selected running speed desired to be maintained, means actuated by said control signals for scheduling admission of fuel to said engine, and means responsive to the speed of said engine for applying only said first control signal to said fuel scheduling means at engine speeds below a predetermined fraction of said selected running speed and similarly applying only said second control signal at engine speed above said predetermined fraction.

29. A device for controlling acceleration and speed of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber therebetween, said device comprising; means producing a first signal variable with the temperature of the combustion gases, means modifying said signal as a function of both engine speed and air temperature at the air inlet to said compressor unit, means producing a first reference signal representative of a selected maximum permissible combustion gas temperature, and means comparing said modified first signal with said reference signal to produce a first control signal variable as the difference therebetween, means producing a second signal variable with the difference between the actual speed of said engine as compared with a selected running speed desired to be maintained; means actuated by said control signals for scheduling admission of fuel to said combustion chamber; and means responsive to the speed of said engine for applying only said first control signal to said fuel scheduling means at engine speeds below a predetermined fraction of said selected running speed and similarly applying only said second control signal at engine speeds above said predetermined fraction.

30. A device for controlling acceleration from idling speed of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber unit therebetween, said device comprising means producing a first signal variable with the temperature of the combustion gases, means producing a reference signal representative of a selected maximum permissible combustion gas temperature, means comparing said signals to produce a control signal variable as the difference therebetween, means actuated by said control signal for scheduling admission of fuel to said combustion chamber unit, means responsive to engine speed for rendering said control signal ineffective when a predetermined engine speed has been reached, and speed dependent means effective at engine speeds above said predetermined speed producing a second control signal and which is applied to said fuel scheduling means.

31. A control device for engines as defined in claim 30 and which further includes means modifying said control signal in accordance with the speed of said engine.

32. A control device for engines as defined in claim 30 and which further includes means modifying said control signal in accordance with the air temperature at the air inlet to said compressor unit.

33. A control device for engines as defined in claim 30 and which further includes means modifying said control signal in accordance with engine speed and air temperature at the air inlet to said compressor unit.

34. A device for controlling acceleration and speed of a combustion gas engine of the type including coupled turbine and compressor units and a combustion chamber unit therebetween, said device comprising; means producing a first signal variable with the temperature of the combustion gases, means modifying said first signal in accordance with the speed of said engine, means producing a first reference signal representative of a selected maximum permissible combustion gas temperature, means comparing said modified signal and said reference signal to produce a first control signal variable as the difference therebetween; means producing a second signal variable with the engine speed, means producing a second reference signal representative of a selected running engine speed desired to be maintained, means comparing said second signal and second reference signal to produce a second control signal; means actuated by said control signals for scheduling admission of fuel to said combustion chamber unit; and means responsive to engine speed for applying only said first control signal to said fuel scheduling means at engine speeds below a predetermined fraction of said selected running speed and similarly applying only said second control signal at engine speeds above said predetermined fraction.

35. A device for controlling acceleration from idling speed of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber therebetween, the combination comprising, means producing a control signal variable with the temperature of the combustion gases, means responsive to the temperature of the air which flows through the engine for varying said control signal inversely as the change in said air temperature, and means responsive to said control signal for scheduling admission of fuel to said combustion chamber in an amount variable inversely as the amplitude of said control signal.

36. An engine control device as defined in claim 35 and which further includes means responsive to engine speed for varying said control signal inversely as the change in engine speed.

37. A device for controlling acceleration from idling speed of a combustion gas turbine engine of the type including coupled turbine and compressor units and a combustion chamber therebetween, the combination comprising, means for producing a control signal variable with the temperature of the combustion gases, means responsive to engine speed for varying said control signal inversely as the change in engine speed, and means responsive to said control signal for scheduling admission of fuel to said combustion chamber in an amount variable inversely as the amplitude of said control signal.

(References on following page)

References Cited in the file of this patent

UNITED STATES PATENTS

Number	Name	Date
2,148,718	Agins	Feb. 28, 1939
2,219,994	Jung	Oct. 29, 1940
2,336,232	Doran	Dec. 7, 1943
2,391,291	Bollo et al.	Dec. 18, 1945
2,457,595	Orr	Dec. 28, 1948
2,463,566	Saldin	Mar. 8, 1949
2,492,472	Fortescue	Dec. 27, 1949

FOREIGN PATENTS

Number	Country	Date
926,065	France	Sept. 22, 1947

(Corresponding Great Britain 601,107, Apr. 28, 1948.)