Aug. 11, 1970 P. H. J. YOUNG 3,523,423

GAS TURBINE ENGINES

Filed March 11, 1968 2 Sheets-Sheet 1

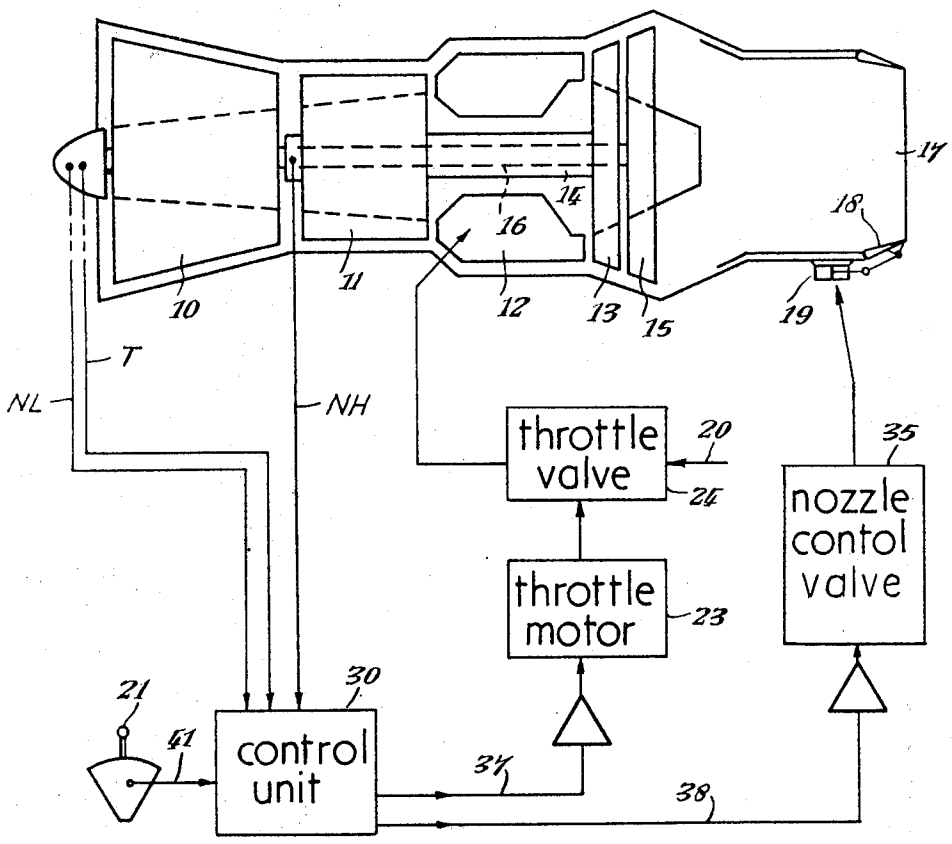


Fig. 1.

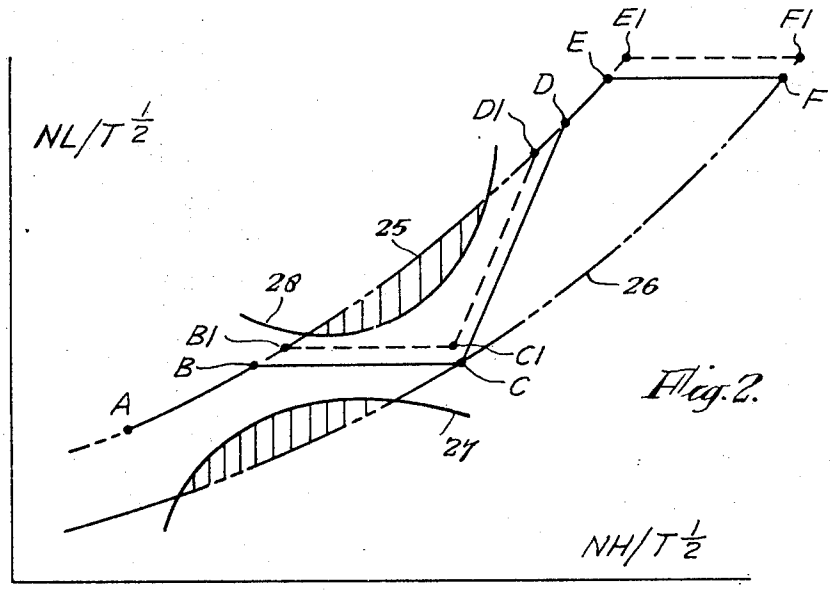


Fig. 2.

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Filed March 11, 1968 2 Sheets-Sheet 2

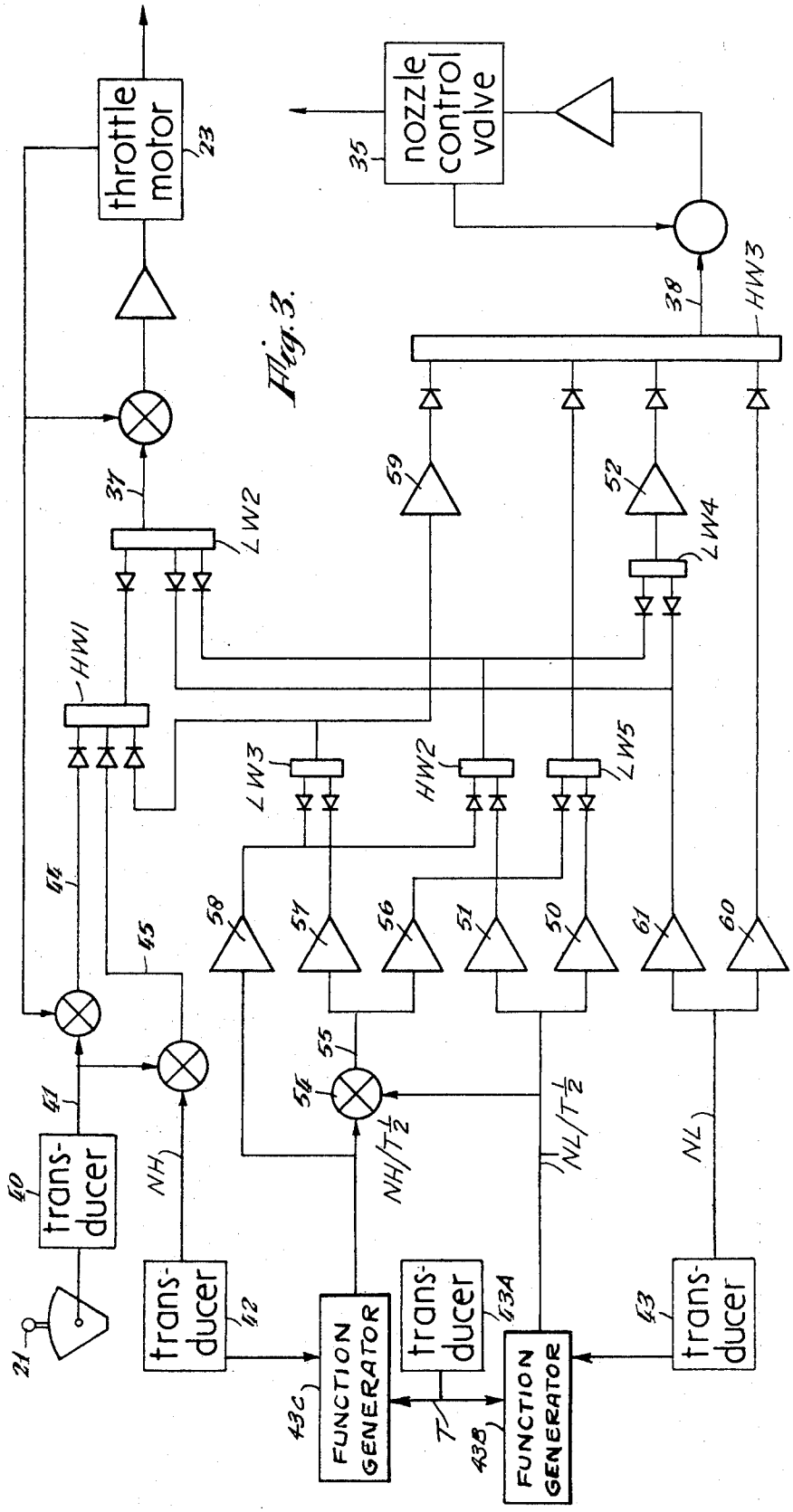


Fig. 3.

United States Patent Office 3,523,423 Patented Aug. 11, 1970

3,523,423

GAS TURBINE ENGINES

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Filed Mar. 11, 1968, Ser. No. 711,958
Claims priority, application Great Britain, Mar. 11, 1967 11,509/67
Int. Cl. F02k 1/18, 3/12; F02c 9/08
U.S. Cl. 60—236 9 Claims

ABSTRACT OF THE DISCLOSURE

The disclosure of this invention pertains to a two-spool gas turbine engine having a system whereby, to avoid surge, the speed of the low pressure compressor is made to conform to a schedule which is a function of the speed of the high pressure compressor. The system includes means for acting on the fuel flow so as to control the speed of the high pressure compressor if the low pressure compressor cannot respond fast enough to the action of the schedule.

This invention relates to multi-spool gas turbine engines. Such engines comprise at least two co-axial compressors being in relation to each other a low and a high pressure compressor, a combustor, a high pressure turbine connected to drive the high pressure compressor, and a low pressure turbine connected to drive the low pressure compressor.

The low pressure compressor must be operated to produce a mass flow matching the flow demanded by the high pressure compressor. It is sometimes difficult to achieve this over the whole operating range of the engine, and it can happen that the one or other of the compressors tends to surge at certain parts of said range particularly during relatively rapid changes in power demand. The object of this invention is to reduce or overcome this difficulty.

According to this invention there is provided in a multi-spool gas turbine engine having high pressure and low pressure compressors and a device for regulating an operating parameter of the low pressure compressor independently of the high pressure compressor; a system of controlling the device, comprising means for generating a signal being a function of an operating parameter of the high pressure compressor, and means responsive to the signal for operating the device to maintain the operating parameter of the low pressure compressor at a predetermined value relative to that of the high pressure compressor.

Preferably said device comprises a variable area nozzle. However, any other means for varying an operating parameter of a compressor may be used, e.g. variable angle inlet guide vanes or a valve for bleeding air from the compressor to atmosphere.

The engine may include a means settable to regulate the mechanical speed of the high pressure compressor, the system including means, responsive to a variation of the operating parameter of the low pressure compressor from said predetermined value by more than a predetermined amount, for acting on the settable means in the sense of opposing each variation.

During rapid changes in power demand said means for acting on the high pressure compressor tend to restrict the operating parameter of the low pressure compressor to the region of said predetermined amount and the compressors can thereby be kept free from surge notwithstanding the transient nature of the operation.

An example of a control system according to this invention will now be described with reference to the accompanying drawings wherein:

FIG. 1 is a block diagram of the control system and a diagrammatic illustration of a gas turbine engine associated therewith.

FIG. 2 is a graph showing the relationship between the speeds of the high and low pressure compressors.

FIG. 3 is a logic diagram of details of the control system.

Referring to the FIG. 1, the engine comprises in flow series a low pressure compressor **10**, a high pressure compressor **11**, combustion chambers **12**, a high pressure turbine **13** connected by a shaft **14** to the compressor **11**, a low pressure turbine **15** connected by a shaft **16** to the compressor **10**, and a nozzle **17**. The elements **10, 15** are also referred to as the "low pressure spool" and the elements **11, 13** as the "high pressure spool" of the engine.

The nozzle comprises pivotal petals **18** movable by means of pneumatic motors **19** to vary the outlet area of the nozzle under the control of a nozzle control valve **35**.

The combustion chambers are supplied with fuel through a line **20**. The rate of fuel flow and thus the power developed by the engine is controlled by means of a pilot's throttle lever **21**, which controls the current supply to an electric motor **23** driving the closure member of a throttle valve **24** in the line **20**.

The speeds of the two compressors depend essentially on the two variables of fuel flow and nozzle area. An increase in fuel flow increases the speed of both spools, and vice versa. A change in nozzle area varies the ratio between the two speeds, the speed of the low pressure compressor being raised relative to that of the high pressure compressor if the nozzle area is increased, and vice versa, this being so especially if the high pressure turbine is choked (as it is at all but relatively low speeds) because then the effect of a change of nozzle area is felt exclusively in terms of a speed change of the low pressure turbine and thus of the low pressure compressor. FIG. 2 shows the relationship between the aerodynamic speeds of the two compressors by two curves **25, 26** which signify respectively the condition when the nozzle area is the maximum and the minimum to which it can be adjusted. The "aerodynamic" speeds of the compressors are given by the ratios $NL/T^{½}$ and $NH/^{½}$, where NL and NH are the mechanical speeds of the low and high pressure compressor, respectively, and T is the total temperature of the air entering the low pressure compressor.

The curve **26** is intersected by a curve **27** defining the surge boundary of the high pressure compressor. This means that there is a speed range of the high pressure compressor at which this compressor is in danger of surge if the nozzle area is more nearly at its minimum. This condition can be avoided by so varying the nozzle area that the speed of the low pressure compressor cannot fall below a line A, B, C. Thereby the low pressure compressor is forced to supply the mass flow necessary to keep the high pressure compressor clear of its surge boundary.

A similar situation exists in respect of the curve **25** which is intersected by a curve **28** defining the surge boundary of the low pressure compressor. Here the position is that the speed of the low pressure compressor must not be allowed to rise above the line B, C or above a line C, D thus to prevent the low pressure compressor from developing a greater mass flow than can be absorbed by the high pressure compressor. This again is done by appropriate adjustment of the nozzle area.

Above the point D, the aerodynamic speed of the low pressure compressor may again follow the curve **25** but the mechanical speed of the low pressure compressor must not rise above a line E, F for reason of mechanical safety.

The curve A to F defines the aerodynamic or mechani-

cal speeds, as the case may be, of the low pressure compressor and of this curve the part B, C, D defines a schedule in accordance with which the aerodynamic speed and thus the mass flow of the low pressure compressor is controlled as a function of that of the high pressure compressor for the purpose of surge control by means of the nozzle.

Under conditions of relatively rapid changes in power demand a change of nozzle area is by itself not sufficient and, as will be seen, an appropriate control of fuel flow is introduced as well.

Reverting to FIG. 1, the control system comprises a control unit **30** connected to the compressors **10**, **11** to receive therefrom a signal **41** defining the position of the lever **21**, signals NL and NH defining the mechanical speeds of the compressors **10** and **11**, and a signal T defining the total temperature of the air entering that compressor.

In the unit **30** there is produced an error signal **37** acting on the throttle motor **23** and defining the difference between the actual fuel flow and that demanded by the setting of the lever **21**. Further, the unit **30** produces an error signal **38** acting on the nozzle control valve **35** and defining the difference between the actual aerodynamic speed of the low pressure compressor **10** and that demanded by the lines B, C, D in FIG. 2. The unit **30** also acts on the signal **37** to modify the demand of the lever **21** under conditions when operation of the nozzle is by itself not sufficient to prevent surge.

Details of the control unit **30** will now be described with reference to FIG. 3. The inputs to the unit **30** comprise a transducer **40** operated by the pilot's lever **21** to produce the signal **41** representing the demand for fuel flow, a transducer **42** operated by the shaft **14** to produce the signal NH, and a transducer **43** operated by the shaft **16** to produce the signal NL. A temperature transducer **43A** supplies the signal T.

In the control unit, signals are related by logic devices known as "highest win gates" and "lowest win gates." A highest win gate is an electrical device having a output proportional to the highest or most positive of two or more inputs. A lowest win gate is an electrical device having an output proportional to the lowest or most negative of two or more inputs. Such devices are well known per se.

At the output side of the control unit, the signal **37** driving the throttle motor **23** is the output of a lowest win gate LW2 and drives the throttle in the open direction when the signal **37** is positive relative to a given level. When the signal **37** is negative relative to that level the motor drives the throttle in the closed direction. The rate of throttle movement depends on the magnitude of the signal **37**. In the absence of an input to LW2 the output signal therefrom is positive and the throttle is therefore normally open.

The signal **38** driving the nozzle operating valve **35** is the output of a highest win gate HW3 and drives the motor **19** to reduce the nozzle area when the signal **38** is positive above a given level, the reverse taking place when the signal **38** is negative. The rate of nozzle movement depends on the magnitude of the signal **38**. The output of the gate HW3 is normally negative so that, in the absence of an input to this gate, the nozzle is at its maximum area.

Reverting to the input side, the fuel demand signal **41** acts on the signal **37** through a highest win gate HW1 and said lowest win gate LW2. The provision of the gate HW1 accords with a requirement for constant fuel flow at low power settings of the lever **21** and for constant speed of the high pressure spool when a specified power setting of the lever **21** is exceeded. This aspect does not require specific discussion except for saying that the demand signal **41** is presented to the gate HW1 in the form of a throttle setting error **44** and a speed error **45** and whichever error is the greater takes control of the output of the gate HW1. Further, as will be seen, the fuel flow can be prevented from falling by a further signal into the gate HW1 or reduced by further signals into the gate LW2.

In the control unit **30** the signals NL and NH are combined through function generators **43B** and **43C**, respectively, with the signal T to produce the signals $NL/T^{½}$ and $NH/T^{½}$. This is well understood per se.

Between the points A, B of the curve A to F, the nozzle is not actively controlled by the control unit and the signal $NL/T^{½}$ follows the curve **25**, the nozzle being at its maximum area in view of the absence of a positive signal at the gate HW3. Between the points B, C the nozzle and the fuel flow are controlled by proportional amplifiers **50**, **51** to keep the signal $NL/T^{½}$ constant as the signal $NH/T^{½}$ varies. Between the points C, D the nozzle and the fuel flow are controlled by proportional amplifiers, **56**, **57** to maintain the signal $NL/T^{½}$ on the slope of the line C, D as the signal $NH/T^{½}$ varies. Between the points D, E the signal $NL/T^{½}$ again follows the curve **25** and, finally, between the points E, F the nozzle and the fuel flow are controlled by proportional amplifiers **60**, **61** to keep the signal NL constant with varying values of the signal $NH/T^{½}$, the line E, F representing a limit to the mechanical speed of the low pressure compressor. The operation along the respective parts of the curve A to F are now described separately and in further detail.

During variation of the signal $NH/T^{½}$ between the points A, B of FIG. 2 the signal $NL/T^{½}$ is determined simply by the nozzle being held in the position of maximum area also referred to as "the fully open position." As will become apparent below, this is done by preventing any positive signal from reaching the gate HW3.

During variation of the signal $NH/T^{½}$ between the points B, C the signal $NL/T^{½}$ is controlled by being kept constant with respect to the signal $NH/T^{½}$. This means that the nozzle area must be progressively reduced as the signal $NH/T^{½}$ increases and vice veresa. To this end the amplifier **50** has an input from the signal $NL/T^{½}$ and is adapted for its output to change from negative to positive when the signal $NL/T^{½}$ rises above the line A, B and vice versa. The amplifier **50** is connected through a lowest win gate LW5 to the gate HW3. The one other input to the gate LW5 is at this stage positive. The amplifier **50** is therefore in control of the gate LW5 and when the output from the amplifier becomes positive the output from the gate LW5 to the gate HW3 goes positive and causes the nozzle area to be reduced, and vice versa. In other words, the amplifier **50** gives rise to an error signal which varies the nozzle area to keep the signal $NL/T^{½}$ constant.

During variation of the signal $NH/T^{½}$ between the points C, D the signal $NL/T^{½}$ is required to vary in accordance with the slope of the line C, D. This is done as follows. The signals $NL/T^{½}$ and $NH/T^{½}$ are fed to a summing junction **54** adapted to produce an error signal **55** which goes positive when the signal $NL/T^{½}$ is higher than the zero datum of the junction and vice versa. It is to be understood that the signals $NL/T^{½}$ and $NH/T^{½}$ fed to the summing junction **54** are in the proportions required to achieve the slope of the line C, D. These proportions are generated by the function generators **43B**, **43C**. The signal **55** is made an input to the amplifier **56** whose output, which is of the same sign as the signal **55**, is connected to the gate LW5. During operation along the lines A, B and B, C the signal $NL/T^{½}$ is bound to be above the zero datum of the junction **54** so that the output from the amplifier **56** is positive and control of the gate LW5 is with the output from the amplifier **50**. However, during operation along the line C, D the output of the amplifier **56** varies around zero while the output of the amplifier **50** tends to remain positive in view of the magnitude of the signal $NL/T^{½}$ above the point C. Control of the gate LW5 is therefore taken over by the amplifier **56** and the nozzle area is progressively en-

larged as the signal $NH/T^{\frac{1}{2}}$ increases, and vice versa, to vary the signal $NL/T^{\frac{1}{2}}$ in accordance with the slope of the line C, D. At the point D the nozzle is in the fully open position.

During variation of the signal $NH/T^{\frac{1}{2}}$ between the points D, E the signal $NL/T^{\frac{1}{2}}$ is bound to be below the zero datum of the junction **54** so that output of the amplifier **56** is negative and the nozzle is held in the open position.

During variation of the signal $NH/T^{\frac{1}{2}}$ between the points E, F it is necessary to prevent the mechanical speed of the low pressure spool from exceeding a safe limit and to this end the nozzle area is varied to keep the signal NL constant. The signal NL is made an input to the amplifier **60** which is adapted to change its output from negative to positive when the signal NL rises above the line E, F and vice versa. The amplifier **60** has an output to the gate HW3 and when that output becomes positive, it becomes the dominant input to the gate HW3 and the nozzle area is reduced. In other words during operation along the line E, F the amplifier **60** gives rise to an error signal which varies the nozzle area to keep the signal $NL/T^{\frac{1}{2}}$ constant.

The foregoing description of the operation along the line A to F applies essentially to steady state conditions, that is conditions in which the rate of fuel flow variation is low, as distinct from transient conditions in which that rate is sufficiently high to require additional means for stabilizing the system against unduly close approach to the surge boundaries of the compressors. In the present example, this means that the signal $NL/T^{\frac{1}{2}}$ must be limited against movement substantially above the line B, C or to the left of the line C, D for relevant values of $NH/T^{\frac{1}{2}}$. It is also desirable to provide a limit by which the signal NL must not exceed the line E, F. The values to which the signals $NL/T^{\frac{1}{2}}$ and NL are limited in this way are defined by the lines B1, C1, D1 and E1, F1 in FIG. 2.

If, during variation of the signal $NH/T^{\frac{1}{2}}$ between the points B, C the signal $NL/T^{\frac{1}{2}}$ should rise above the line B1, C1, there is an acute danger of surge of the low pressure compressor. This situation arise essentially during a sharp acceleration of the engine but could also arise on account of some fault inhibiting a reduction in nozzle area. The actions to be taken is to reduce the fuel flow so as to reduce the demand for speed of the low pressure compressor. Optionally one may also initiate a signal to reduce the nozzle area to strengthen the demand already being made by the amplifier **50** for a reduced nozzle area. For these purposes the signal $NL/T^{\frac{1}{2}}$ is connected to the amplifier **51** which is adapted to change its output from positive to negative when the signal $NL/T^{\frac{1}{2}}$ exceeds the line B1, C1, and vice versa. The output of the amplifier **51** is made an input to a highest win gate HW2 whose one other input is at this stage fully negative so that the amplifier **51** dominates the gate HW2. The gate HW2 has an output to the gate LW2 and to a lowest win gate LW4 whose one other input is at this stage positive. In consequence the gate LW2 acts on the signal **37** to reduce fuel flow to prevent the $NL/T^{\frac{1}{2}}$ exceeding the line B1, C1. The gate LW4 has an output to a trigger amplifier **52** whose output leads to the gate HW3. The output of the amplifier **52** changes from fully negative to fully positive, and dominates the gate HW3, when the output of the gate HW2 becomes negative, and vice versa. Hence, when the signal $NL/T^{\frac{1}{2}}$ rises above the line B1, C1 the nozzle is subjected to a sharp signal to reduce its area.

When operating along the line C, D the signal $NL/T^{\frac{1}{2}}$ can become excessively high with respect to the signal $NH/T^{\frac{1}{2}}$ and appear to the left of the line C1, D1. This is not likely to occur during acceleration when the speed of the low pressure compressor tends to lag behind that of the high pressure compressor. But during sharp deceleration, e.g. a sharp reduction in fuel demand by the pilot, the low pressure compressor is in acute danger of surging because it may fail to slow down by an amount greater than can be corrected by the positive output of the amplifier **56**. The steps taken to avoid this situation are to inhibit the rate at which fuel flow is reduced, i.e. the rate at which the speed of the high pressure compressor is reduced, and optionally simultaneously to reduce the nozzle area to enocourage a reduction in the speed of the low pressure compressor. Since the inhibition on the reduction in fuel flow may occur simultaneously with the call for fuel reduction made by the amplifier **51** in respect of the line B1, C1, it is necessary to cancel the action of the latter amplifier when operating in the vicinity of line C, D. To this end the signal $NH/T^{\frac{1}{2}}$ is connected to a trigger amplifier **58** set to change from a wholly negative to a wholly positive position output when the signal $NH/T^{\frac{1}{2}}$ is above the point C1. The output of the amplifier **58** is connected to the gate HW2 and, when positive, this output takes control of the gate HW2 way from the amplifier **51**. The resultant wholly positive output of the gate HW2 is of no effect because it is stopped by the diodes of the gates LW4 and LW2. Having thus disabled the amplifier **51**, it is now possible to prevent a fuel reduction. This is done by the amplifier **57** which has an input from the signal **55** and which is set to change its output from negative to positive when the error **55** rises above zero by more than an amount causing the signal $NL/T^{\frac{1}{2}}$ to cross to the left of the line C1, D1. The amplifier **57** also has an output to a lowest win gate LW3 whose only other input is from the amplifier **58** whose output, when positive, connects the amplifier **57** through the gate LW3 to the gate HW1. When the output of the amplifier **57** becomes positive, there is put into the gate HW1 a signal which is positive relative to the signals **44**, **45** which, during deceleration, tend to be negative. Thus the fuel flow is prevented from falling against the demand for less fuel by the pilot's lever. The output from the amplifier **57** may also be connected to a trigger amplifier **59** adapted to change from a wholly negative to a wholly positive output when the signal from the amplifier **57** becomes positive. The output of the amplifier **59** is connected to the gate HW3 to impart a closure movement to the nozzle similar to the action produced by the amplifier **52**. When the output from the amplifier **57** is negative there is no effect on either of the gates HW1 or HW3.

Should the signal NL rise above the line, E1, F1 progressive reduction in fuel flow and a sharp reduction of nozzle area is carried out through the amplifier **61** whose input is connected to the signal NL and which is adapted for its output to change from positive to negative when the input rises above the line E1, F1. The output of the amplifier **61** is connected to the gate LW2 so that when this output becomes negative the fuel flow is reduced. The output of the amplifier **61** is also connected to the gate LW4 to activate the amplifier **52** to sharply reduce the nozzle area in the same way as was described with reference to the amplifier **51**.

It will be seen that the amplifier **50**, or the summing junction **54** and amplifier **56**, constitute means for producing an error signal, i.e. the output of the amplifiers **50** or **56**, indicative of the difference between the actual aerodynamic speed of the low pressure compressor and that defined by the schedule at B, C or C, D; and that the valve **35** and motor **19** constitute a means for operating the nozzle to cause the error signal to tend to zero.

It is clear that the line B1, C1, D1 defines a schedule serving a purpose similar to that served by the schedule B, C, D but in association with the amplifiers **51**, **57** and acting on the fuel flow in addition to action on the nozzle.

Referring back to the lines B, C and B1, C1, it will be understood that these lines can also be made linear functions of $NH/T^{\frac{1}{2}}$, e.g. in a manner similar to the lines C, D and C1, D1.

What I claim is:

1. In a multi-spool gas turbine engine having high and low pressure compressors and an exhaust nozzle whose area is variable to vary the mechanical speed of the low pressure compressor; a system for controlling the nozzle comprising:

(a) first control means responsive to a first range of corrected speed to the high pressure compressor for positioning the nozzle in accordance with a first speed relationship of corrected speeds of the high and low pressure compressors,

(b) second control means, responsive to a second range of corrected speed of the high pressure compressor for positioning the nozzle in accordance with a second speed relationship of the high and low pressure compressors, and

(c) means for automatically changing from control by the first to control by the second control means responsive to the corrected speed of the high pressure compressor changing from the first to the second range and vice versa.

2. System according to claim **1**, wherein the first means comprise a device (HW3) for causing the nozzle to be immovable at one end of its range of movement, and the second means comprise a closed loop control for continually varying the nozzle position in response to variation in the corrected speed of the high pressure compressor.

3. System according to claim **1**, wherein at least the second control means comprise a computer including means **43B** for forming from values of mechanical speed and of temperature fed thereto a value ($NL/T\frac{1}{2}$) of the corrected speed of the low pressure compressor, means **(50)** for sensing deviation of said value from a datum value, and means (LW5, HW3) for varying the nozzle to keep said value substantially at said datum.

4. System according to claim **1**, wherein at least the second means comprise a computer including means for forming from values of mechanical speeds and from temperatures fed thereto values ($NH/T\frac{1}{2}$, $HL/T\frac{1}{2}$) of the corrected speeds of the high and of the low pressure compressor, means **(54)** for forming an error signal **(55)** being zero when the values ($NH/T\frac{1}{2}$, $NL/T\frac{1}{2}$) have a determined ratio, means (LW5, HW3) for varying the nozzle to cause error signal to tend to zero, and means (LW5) for rendering the error signal **(55)** inoperative outside said speed range.

5. System according to claim **1**, comprising means **(19)** limiting the movement of the nozzle to positions of maximum and minimum flow area, wherein at least one of said control means comprises a closed loop control for continually varying the nozzle position in response to variation in the corrected speed of the high pressure compressor, and wherein the range of the corrected speed of the high pressure compressor is determined by said means **(19)** for limiting the movement of the nozzle.

6. System according to claim **5**, having means (HW3) for tending to maintain the nozzle in the position of maximum flow area, and wherein means for initiating the last mentioned closed loop control comprise a device **(50)** responsive to the corrected speed of the low pressure compressor exceeding a determined value.

7. System according to claim **5**, having means (HW3) for tending to maintain the nozzle in the position of maximum flow area, and wherein means for initiating the last mentioned closed loop control comprise a device **(54)** responsive to a determined ratio of corrected speeds of the high and low pressure compressors.

8. In a gas turbine engine having high pressure and low pressure spools and an exhaust nozzle which is controllable to vary the flow area thereof; a system comprising:

(a) during a first range of corrected speed of the high pressure spool being a range next above idling speed, controlling the nozzle for the latter to be held at the position of maximum flow area;

(b) during a second range of corrected speed of the high pressure spool being a range next above the first range, controlling the nozzle for the flow area thereof to be progressively reduced to maintain the corrected speed of the low pressure spool substantially constant;

(c) during a third range of corrected speed of the high pressure spool being a range next above the second range, controlling the nozzle for the flow area thereof to be progressively enlarged to maintain constant a given ratio of corrected speeds of the high and low pressure spools.

9. In a gas turbine engine having high pressure and low pressure spools and an exhaust nozzle which is controllable to vary the flow area thereof; a system comprising:

(a) during a first range of corrected speed of the high pressure spool being a range next above idling speed, means for controlling the nozzle of the latter to be held at the position of maximum flow area;

(b) during a second range of the corrected speed of the high pressure spool being a range next above the first range, means for controlling the nozzle for the flow area thereof to be progressively reduced to maintain a corrected speed of the low pressure spool substantially constant;

(c) during a third range of corrected speed of the high pressure spool being a range next above the second range, means for controlling the nozzle for the flow area thereof to be progressively enlarged to maintain constant a given ratio of corrected speeds of the high and low pressure spools.

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