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(54) **COMPRESSOR STALL AVOIDANCE**

VERMEIDUNG DES PUMPENS EINES VERDICHTERS

EVITEMENT DU CALAGE DE COMPRESSEURS

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Description**Technical Field**

5 **[0001]** This invention relates to techniques for diagnosing and avoiding stall in rotary compressors, such as aircraft jet engines.

Background of the Invention

10 **[0002]** In a dynamic rotary compressor operating under normal, stable flow conditions, the flow through the compressor is essentially uniform around the annulus, i.e., it is axisymmetric, and the annulus-averaged flow rate is steady. Generally, if the compressor is operated too close to the peak pressure rise on the compressor pressure rise versus mass flow, constant speed performance map, disturbances acting on the compressor may cause it to encounter a region on the performance map in which fluid dynamic instabilities develop, known as rotating stall and/or surge. This region is bounded on the compressor performance map by the surge/stall line. The instabilities degrade the performance of the compressor and may lead to permanent damage, and thus they should be avoided.

15 **[0003]** Rotating stall can be viewed as a two-dimensional phenomena that produces a localized region of reduced or reversed flow through the compressor that rotates around the annulus of the flow path. The region is termed a "stall cell" and typically extends axially through the compressor. Rotating stall produces reduced output (as measured in annulus-averaged pressure rise and mass flow) from the compressor. In addition, as the stall cell rotates around the annulus it loads and unloads the compressor blades and may induce blade fatigue failure. Surge is a one-dimensional phenomena defined by oscillations in the annulus-averaged flow through the compressor. Under severe surge conditions, reversal of the flow through the compressor may occur. Both types of instabilities should be avoided, particularly in aircraft applications.

25 **[0004]** In practical applications, the closer the operating point is to the peak pressure rise, the less the compression system can tolerate a given disturbance level without entering rotating stall and/or surge. Triggering rotating stall results in a sudden jump (within 1-3 rotor revolutions) from a state of high pressure rise, efficient, axisymmetric operation to a state of reduced pressure rise, inefficient, non-axisymmetric operation. Returning the compressor to axisymmetric operation (i.e., eliminating the rotating stall region) requires lowering the operating line on the compressor performance map to a point well below the point at which the stall occurred. In practical applications, the compressor may have to be shut down and restarted to eliminate (or recover from) the stall due to that stall hysteresis. Triggering a surge produces a similar degradation of performance and operability, but surge arises for different reasons.

30 **[0005]** Because of those potential instabilities, compressors are typically operated with a "stall margin." Stall margin is a measure of the ratio between peak pressure rise, i.e., pressure rise at stall, and the pressure ratio on the operating line of the compressor for the current flow rate. In theory, the greater the stall margin, the larger the disturbance that the compression system can tolerate before entering stall and/or surge. Thus, a compressor design objective is to incorporate enough stall margin to avoid operating in a condition in which an expected disturbance is likely to trigger stall and/or surge. In gas turbine engines used to power aircraft, stall margins of fifteen to thirty percent are common. Since operating the compressor at less than peak pressure rise carries with it a reduction in operating efficiency and performance, there is a trade off between stall margin and performance. Stall margin can be reduced by engine operating conditions, for instance aircraft pitch and yaw and acceleration (conditions that momentarily change increase current pressure) and over time from component wear, for instance enlarged distances between compressor blade tips and the compressor end wall.

Disclosure of the Invention

45 **[0006]** An object of the present invention is to avoid compressor stall, especially in aircraft jet engines.

50 **[0007]** A method for controlling the acceleration mode of a gas turbine engine is known from European Patent Application EP-A2-0401152. The system allows the engine to accelerate with an adequate stall margin by controlling the flow of fuel to the burner, in response to certain engine operating parameters under acceleration.

[0008] From a first aspect, the present invention provides a controller for a rotary compressor as claimed in claim 1.

[0009] From a second aspect, the invention provides a method for avoiding stall in a rotary compressor as claimed in claim 10.

55 **[0010]** In a preferred embodiment of the present invention, compressor flow is sensed with one or more pressure sensors to produce a signal that passed through a bandpass filter having a lower roll-off between .01 and 1 of N2 (compressor rotational frequency) and an upper roll-off between 1 and 10 of N2. The output from the filter is smoothed and compared with a "design value" for compressor flow unsteadiness, producing an error that is integrated. One or more compressor bleed valves are opened when the integral exceeds a preset threshold.

[0011] In a first embodiment of the present invention, compressor bleed valves are opened for a fixed duration when the threshold is exceeded.

[0012] In a second embodiment of the present invention, when the threshold is exceeded and the bleed valves are opened the design value is temporarily changed (e.g., reduced) until the bleed valves close.

[0013] A feature of the invention, stemming from the invention's capability of detecting very early signs of rotating stall, is that a stall controller employing the invention can be used to improve operation of a compression (pumping) system having a compressor susceptible to rotating stall under certain circumstances. A feature of the invention is that it can be used in gas turbine engines and cooling systems, such as some air conditioning systems or refrigeration systems.

[0014] The foregoing and other objects, features and advantages of the present invention will become more apparent from the following description and drawings.

Brief Description of the Drawings

[0015]

Fig. 1 is a functional diagram of a gas turbine engine employing a static pressure sensor and signal processor to control the opening and closing of compressor bleed valves to avoid stall using the time varying output from the pressure sensor according to the present invention.

Fig. 2 shows various compressor stages, compressor flow static pressure sensors, bleed valve locations and signal processing steps to control the opening and closing of the bleed valves according to the present invention.

Fig. 3 shows transfer functions or operations used in one of the steps shown in Fig. 2.

Fig. 4, a three dimensional plot of the magnitude of the pressure fluctuations and N2 and the duration of the fluctuation, shows the pressure fluctuations at N2 that are used for engine diagnostics according to the present invention.

Fig. 5, a three dimensional plot of the magnitude of the pressure fluctuations and N2 and the duration of the fluctuation, shows the pressure fluctuations that typically appear at lower frequencies (below N2) to which prior art stall detection devices typically respond.

Best Mode for Carrying Out the Invention

Active Stall Avoidance

[0016] Fig. 1 shows a bypass gas turbine turbofan engine 10 that uses a static pressure sensor 12 to provide a signal PR1 with characteristics of the compressor flow 14 present at a compressor stage location, for example between the eight and ninth compressor stages. The signal PR1 is supplied to a signal processor (SP) 16, which can be assumed to include a central processing unit and associated memory programmed to cyclically perform computation steps using the signal PR1 and the control/transfer functions 20, 22, 24 and 26 in Fig. 2 to produce a signal A_{con} .

[0017] The signal processor also receives a compressor speed (N2) signal, which represents the compressor rotational speed or frequency (i.e., rotor frequency). The signal A_{con} controls the opening of compressor bleed valves 18 using the following control law, which will be explained in more detail using the software function block diagrams in Fig. 2 and Fig. 3:

$$K_3 \int (\alpha_t - \alpha_1) dt \Big|_0^{\alpha_{max}} \quad \text{Equation 1}$$

In this equation 1, α_1 = an instantaneous level of unsteadiness in flow properties as manifested in the pressure signal PR1 and α_k is a stored or "design" value for the instantaneous level of unsteadiness.

[0018] In Fig. 1, a so-called "FADEC" or "Full Authority Digital Electronic Control" 28 controls fuel flow to the engine combustors 2 as a function of a power lever advance PLA at a cockpit located power control 4. The fuel control may be assumed to include a signal processor for controlling the fuel flow based on a variety of engine operating parameters and, while a separate signal processor 16 to carry out the special sequences associated with the invention has been shown, it is conceivable that a FADEC can be programmed to perform those operations and produce the A_{con} signal to control the bleed valves 18.

[0019] Referring to Fig. 2, it can be observed that a compressor includes a plurality of stages, that the bleed valves 18 are selectively located at certain stages and that the static pressure sensor 12 is ahead of those stages (upstream

in the compressor flow), although in some applications the sensor or sensors 12 may be located behind (downstream) from the bleed valves 18. It should be assumed that the signal processor 16 is programmed to carry out steps that achieve the functions of blocks 20, 22, 24 and 26. The pressure signal PR1, produced by the sensor 12, will have a time varying characteristic, creating a compressor flow 14 signature, including an indication of the flow unsteadiness along with flow and sensor noise. The pressure signal PR1 is narrowly filtered at block 20, the bandpass frequency ranging from $1N_2$ to N_2 with 2-pole roll-offs at the upper and lower frequencies. An effect is smoothing the signal PR1. The output from the filter function 20, signal PR2, is used in an absolute value 22 function to produce absolute value signal PR2 for the spectrum of information passed through the filter function 20. To remove undesirable noise in the signal PR2, the output from the block 22 is applied to a low pass filter with a roll off at 1Hz, producing the signal PR3, which in effect is measure of the unsteady flow condition associated with an imminent compressor stall, in other words remaining stall margin. The next block 26 starts the operations shown in Fig. 3. At operation 30 the precursor PR3 is subtracted from a stored value A_{max} (block 32), which is a maximum or design value for the precursor and if exceeded manifests an unstable compressor flow in the value of signal Error1. Assuming that the output from scaling block 34 is zero, the output, Error 2, from a second summer 36 would be Error1. The value for Error 2 is integrated at operation 38. The output from the integration step is limited at operation 40 and the output A_{int} (from the limiter 40) is scaled with operation 42, producing the bleed control output signal A_{con} . At the logic operation 44, the bleed valves 18 are commanded to open completely if A_{con} has exceeded a stored threshold; otherwise, the bleed valves 18 remain completely closed. The block 44 should be capable of performing either of the following operations once the bleed valves are opened. It can provide a signal to reduce the value of A_{max} slightly, e.g., by 10 percent while the bleed valves are open and return A_{max} to its full value when the bleed valves close again (the open signal is discontinued). Alternatively, as shown by the dotted block, a timer function 44a can be employed to open the bleed valves for a fixed interval when the A_{con} signal is produced. The output from the operation 40 is subtracted from the output from the integrator operation 38 at summer 46, and the error from the summer 46 is scaled with operation 34 and applied to the summer 36, which reduces Error2, preventing the integrator operation from "winding up" beyond the value of A_{int} over time. It can be appreciated that the bleed valves 18 will rapidly open when the precursor (signal PR1) indicates a flow condition near the stall boundary; that is, the time varying flow characteristics, normally found at the early stages of a rotating stall, are within the bandwidth of filter 20 and last long enough for A_{con} to exceed the threshold.

[0020] Referring to FIG.4, at the rotational frequency of the rotor disk the pressure fluctuations (the signal TP) appear hundreds of rotor revolutions prior to an actual stall and/or surge. In Fig. 4, the X-axis shows the time in seconds before the stall, the stall and/or surge occurring approximately at zero (0) seconds. The Z-axis shows the strength of the pressure disturbance in pounds per square inch squared (psi^2) or amplitude squared. The Y-axis indicates the engine order, the frequency of the pressure fluctuation (the value of TP) divided by N_2 (the rotational frequency of the rotor disk), the value one (1) being the rotational frequency of the rotor disk and one half (0.5) being one half of the rotational frequency of the rotor disk. This demonstrates that the pre-stall pressure disturbance at N_2 can be detected a few seconds in advance of the stall and/or surge. The value of N_2 in this example is approximately one hundred (100) revolutions per second. Thus, monitoring the pressure fluctuations at N_2 detects the pre-stall condition several hundred rotor revolutions prior to an actual stall.

[0021] Such early detection affords sufficient warning to take corrective action to prevent or minimize the stall and/or surge. The state of the prior art has concentrated on monitoring pressure fluctuations at 30-70% of the rotational frequency of the rotor disk, or 0.3-0.7 of the engine order shown on Y-axis. As can be seen in Fig.5, the prior art technique allowed warning of the upcoming stall and/or surge merely a few rotor revolutions in advance of the actual stall. Fig.5 is analogous to Fig.4, but is scaled to show rotating stall disturbances at approximately one half (0.5) or fifty percent (50%) of the rotational frequency of the rotor disk.

[0022] The preferred embodiment described herein used an unsteady pressure quantity as a form of measurement. Other unsteady flow parameters can be monitored to predict the onset of a stall and/or surge. For example, gas density, velocity, temperature, or any other unsteady flow quantity can be monitored to determine the onset of the stall and/or surge. The velocity can be measured by using hot wire anemometers or a pitot-static tube. The temperature can be measured by using a fine wire thermocouple.

[0023] The test or diagnostic equipment described and depicted in Fig. 2 is an example of test equipment that can be used to monitor the amplitude of pressure fluctuations according to the invention. Other equipment can be substituted for monitoring the pressure fluctuations within the compressor. For example, the data acquisition system can be either a digital data acquisition system, digital tape, FM analog tape or any other type of a system having capability of recording the pressure disturbances (sensor output) with sufficient frequency bandwidth to resolve the disturbances to rotational frequency of the rotor disk. For example, software packages that can be used in the analysis of the pressure and rotor speed data are MATLAB® program, by The Math Works, Inc. of Natick, Massachusetts, and the SNAP-MASTER® setup program by Hem Data Corporation of Southfield, MI. DAQBOOK® data acquisition hardware made by Iotech of Cleveland, Ohio has been used to produce the outputs with those programs.

Claims

1. A controller for a rotary compressor having a compressor bleed valve (18), **characterized by:**

first means (12) for providing a first time varying signal (PR1) manifesting compressor flow;
 second means (20) for providing a second signal (PR2) manifesting the magnitude of said first signal between
 a first frequency that is less than compressor rotational speed and a second frequency that is greater than or
 equal to said compressor rotational speed; and
 signal processing means (24,26) for providing a first processor signal from said second signal that manifests
 a difference between the magnitude of said second signal and a stored value (32) for said second signal, for
 integrating said difference to produce a control signal, and for producing a bleed signal (A_{CON}) to open the
 compressor bleed valve (18) if said control signal exceeds threshold value.

2. The controller described in claim 1, further **characterized in that** said first means comprises a static pressure
 sensor (12) located in a compressor stage.

3. The controller described in claim 1, further **characterized in that:**

said signal processing means (24,26) comprises means for producing said bleed signal (A_{CON}) for a selected
 time interval.

4. The controller described in claim 1, further **characterized in that** said second means (20) has 2-pole roll-offs at
 said first and second frequencies.

5. The controller described in claim 1, further **characterized in that** said first frequency is .1 of compressor rotational
 speed.

6. The controller described in claim 1, further **characterized in that** said first frequency is between .01 and 1 times
 said rotational frequency and said second frequency is between 1 and 10 times said rotational frequency.

7. The controller described in claim 6 further **characterized in that** said signal processing means (24,26) comprises
 means (44a) for producing said bleed signal (A_{CON}) for a fixed time interval.

8. The controller described in claim 1 further **characterized in that** said signal processing means (24,26) comprises
 means (44) for changing the magnitude of said stored value (32) to a temporary value as said bleed signal (A_{CON})
 is produced.

9. The controller described in claim 8 further **characterized in that** said temporary value is less than the magnitude
 of said stored value (32) when said bleed signal is produced.

10. A method for avoiding stall in a rotary compressor, **characterized by:**

sensing the magnitude (PR3) of the time varying characteristics of compressor flow at a bandwidth around the
 rotational frequency of the compressor;
 producing an integral value (38) by integrating the difference between said magnitude (PR3) and a design
 value (32) for said magnitude; and
 increasing compressor mass flow when said integral value (38) exceeds a threshold value.

11. The method described in claim 10, further **characterized by** increasing mass flow for fixed duration of time.

12. The method described in claim 10, further **characterized by** reducing said design value (32) while said integral
 value (38) is produced.

13. The method described in claim 10, further **characterized in that** said bandwidth has lower frequency roll-off at .
 01 to 1 times said rotational frequency and an upper frequency roll-off at 1 to 10 times said rotational frequency.

Patentansprüche

1. Steuerung für einen Rotationsverdichter mit einem Verdichter-Zapfluftventil (18), **gekennzeichnet durch:**

eine erste Einrichtung (12) zum Bereitstellen eines ersten zeitlich veränderlichen Signals (PR1), welches die Verdichterströmung manifestiert;
 eine zweite Einrichtung (20) zum Bereitstellen eines zweiten Signals (PR2), welches die Größe des ersten Signals zwischen einer ersten Frequenz, die niedriger ist als die Verdichterdrehzahl, und einer zweiten Frequenz, die größer oder gleich der Verdichterdrehzahl ist, manifestiert; und
 eine Signalverarbeitungseinrichtung (24, 26) zum Beliefern eines ersten Prozessorsignals aus dem zweiten Signal, welches eine Differenz zwischen der Größe des zweiten Signals und einem gespeicherten Wert (32) für das zweite Signal manifestiert, zum Integrieren der Differenz, um ein Kontrollsignal zu erzeugen und zum Erzeugen eines Zapfluttsignals (A_{CON}), um das Verdichter-Zapfluftventil (18) zu öffnen, wenn das Kontrollsignal einen Schwellwert überschreitet.

2. Steuerung nach Anspruch 1, ferner **dadurch gekennzeichnet, dass** die erste Einrichtung einen statischen Drucksensor (12) aufweist, der in einer Verdichterstufe angeordnet ist.

3. Steuerung nach Anspruch 1, ferner **dadurch gekennzeichnet, dass** die Signalverarbeitungseinrichtung (24, 26) Mittel zum Erzeugen des Zapfluttsignals (A_{CON}) für ein ausgewähltes Zeitintervall aufweist.

4. Steuerung nach Anspruch 1, ferner **dadurch gekennzeichnet, dass** die zweite Einrichtung (20) zwei-poliges Abgleiten bei der ersten und zweiten Frequenz hat.

5. Steuerung nach Anspruch 1, **dadurch gekennzeichnet, dass** die erste Frequenz 0.1 der Verdichterdrehzahl ist.

6. Steuerung nach Anspruch 1, ferner **dadurch gekennzeichnet, dass** die erste Frequenz zwischen 0.01 und 1 Mal der Rotationsfrequenz und die zweite Frequenz zwischen 1 und 10 Mal der Rotationsfrequenz ist.

7. Steuerung nach Anspruch 6, ferner **dadurch gekennzeichnet, dass** die Signalverarbeitungseinrichtung (24, 26) Mittel (44a) zum Erzeugen des Zapfluttsignals (A_{CON}) für ein festgesetztes Zeitintervall aufweist.

8. Steuerung nach Anspruch 1, ferner **dadurch gekennzeichnet, dass** die Signalverarbeitungseinrichtung (24, 26) Mittel (44) zum Ändern der Größe des gespeicherten Werts (32) zu einem temporären Wert, wenn das Zapfluttsignal (A_{CON}) erzeugt wird, aufweist.

9. Steuerung nach Anspruch 8, ferner **dadurch gekennzeichnet, dass** der temporäre Wert geringer ist als die Größe des gespeicherten Werts (32), wenn das Zapfluttsignal erzeugt wird.

10. Verfahren zum Vermeiden von Strömungsabriss in Rotationsverdichtern, **gekennzeichnet durch:**

Erfassen der Größe (PR3) des zeitlich sich ändernden charakteristischen Werts der Verdichterströmung bei einer Bandbreite um die Rotationsfrequenz des Verdichters;
 Erzeugen eines Integralwerts (38) **durch** Integrieren der Differenz zwischen der Größe (PR3) und einem Konstruktionswert (32) für die Größe; und
 Erhöhen der Verdichtermassenströmung, wenn der Integralwert (38) einen Schwellwert überschreitet.

11. Verfahren nach Anspruch 10, ferner **gekennzeichnet durch** Erhöhen der Massenströme für eine festgesetzte Zeitdauer.

12. Verfahren nach Anspruch 10, ferner **gekennzeichnet durch** Verringern des Konstruktionswerts (32), während der Integralwert (38) erzeugt wird.

13. Verfahren nach Anspruch 10, ferner **dadurch gekennzeichnet, dass** die Bandbreite ein Abgleiten der unteren Frequenz bei 0.01 bis 1 Mal der Rotationsfrequenz und ein Abgleiten der oberen Frequenz bei 1 bis 10 Mal der Rotationsfrequenz hat.

Revendications

1. Dispositif de commande d'un compresseur rotatif comportant une soupape de soutirage de compresseur (18), **caractérisé par** :

un premier moyen (12) destiné à délivrer un premier signal variant dans le temps (PR1) indiquant l'écoulement de compresseur ;
 un deuxième moyen (20) destiné à délivrer un deuxième signal (PR2) indiquant l'amplitude dudit premier signal entre une première fréquence qui est inférieure à la vitesse de rotation du compresseur et une deuxième fréquence qui est supérieure ou égale à ladite vitesse de rotation de compresseur ; et
 un moyen de traitement de signal (24, 26) destiné à délivrer un premier signal traité à partir dudit deuxième signal qui indique une différence entre l'amplitude dudit deuxième signal et une valeur mise en mémoire (32) dudit deuxième signal, à intégrer ladite différence pour produire un signal de commande et à produire un signal de soutirage (ACON) pour ouvrir la soupape de soutirage de compresseur (18) si ledit signal de commande dépasse la valeur de seuil.

2. Dispositif de commande selon la revendication 1, **caractérisé en outre en ce que** ledit premier moyen comprend un capteur de pression statique (12) situé dans un étage de compresseur.

3. Dispositif de commande selon la revendication 1, **caractérisé en outre en ce que** :

ledit moyen de traitement de signal (24, 26) comprend un moyen destiné à produire ledit signal de soutirage (ACON) pendant un intervalle de temps choisi.

4. Dispositif de commande selon la revendication 1, **caractérisé en outre en ce que** ledit deuxième moyen (20) possède des coupures bipolaires auxdites première et deuxième fréquences.

5. Dispositif de commande selon la revendication 1, **caractérisé en outre en ce que** ladite première fréquence est égale à 0,1 fois la vitesse de rotation du compresseur.

6. Dispositif de commande selon la revendication 1, **caractérisé en outre en ce que** ladite première fréquence est située entre 0,01 et 1 fois ladite fréquence de rotation et ladite deuxième fréquence est située entre 1 et 10 fois ladite fréquence de rotation.

7. Dispositif de commande selon la revendication 6, **caractérisé en outre en ce que** ledit moyen de traitement de signal (24, 26) comprend un moyen (44a) destiné à produire ledit signal de soutirage (ACON) pendant un intervalle de temps fixe.

8. Dispositif de commande selon la revendication 1, **caractérisé en outre en ce que** ledit moyen de traitement de signal (24, 26) comprend un moyen (44) destiné à modifier l'amplitude de ladite valeur mise en mémoire (32) en une valeur temporaire lors de la production dudit signal de soutirage (ACON) .

9. Dispositif de commande selon la revendication 8, **caractérisé en outre en ce que** ladite valeur temporaire est inférieure à l'amplitude de ladite valeur mise en mémoire (32) lors de la production dudit signal de soutirage.

10. Procédé destiné à éviter tout calage dans un compresseur rotatif, **caractérisé par** les étapes consistant à :

détecter l'amplitude (PR3) des caractéristiques variant dans le temps de l'écoulement de compresseur à une largeur de bande entourant la fréquence de rotation du compresseur ;
 produire une valeur intégrale (38) en intégrant la différence entre ladite amplitude (PR3) et une valeur de calcul (32) de ladite amplitude ; et
 augmenter le débit massique de compresseur lorsque ladite valeur intégrale (38) dépasse une valeur de seuil.

11. Procédé selon la revendication 10, **caractérisé en outre par** l'étape consistant à augmenter le débit massique pendant une durée fixe.

12. Procédé selon la revendication 10, **caractérisé en outre par** l'étape consistant à réduire ladite valeur de calcul (32) pendant la production de ladite valeur intégrale (38).

- 13.** Procédé selon la revendication 10, **caractérisé en outre en ce que** ladite largeur de bande possède une fréquence de coupure inférieure comprise entre 0,01 et 1 fois ladite fréquence de rotation et une fréquence de coupure supérieure comprise entre 1 et 10 fois ladite fréquence de rotation.

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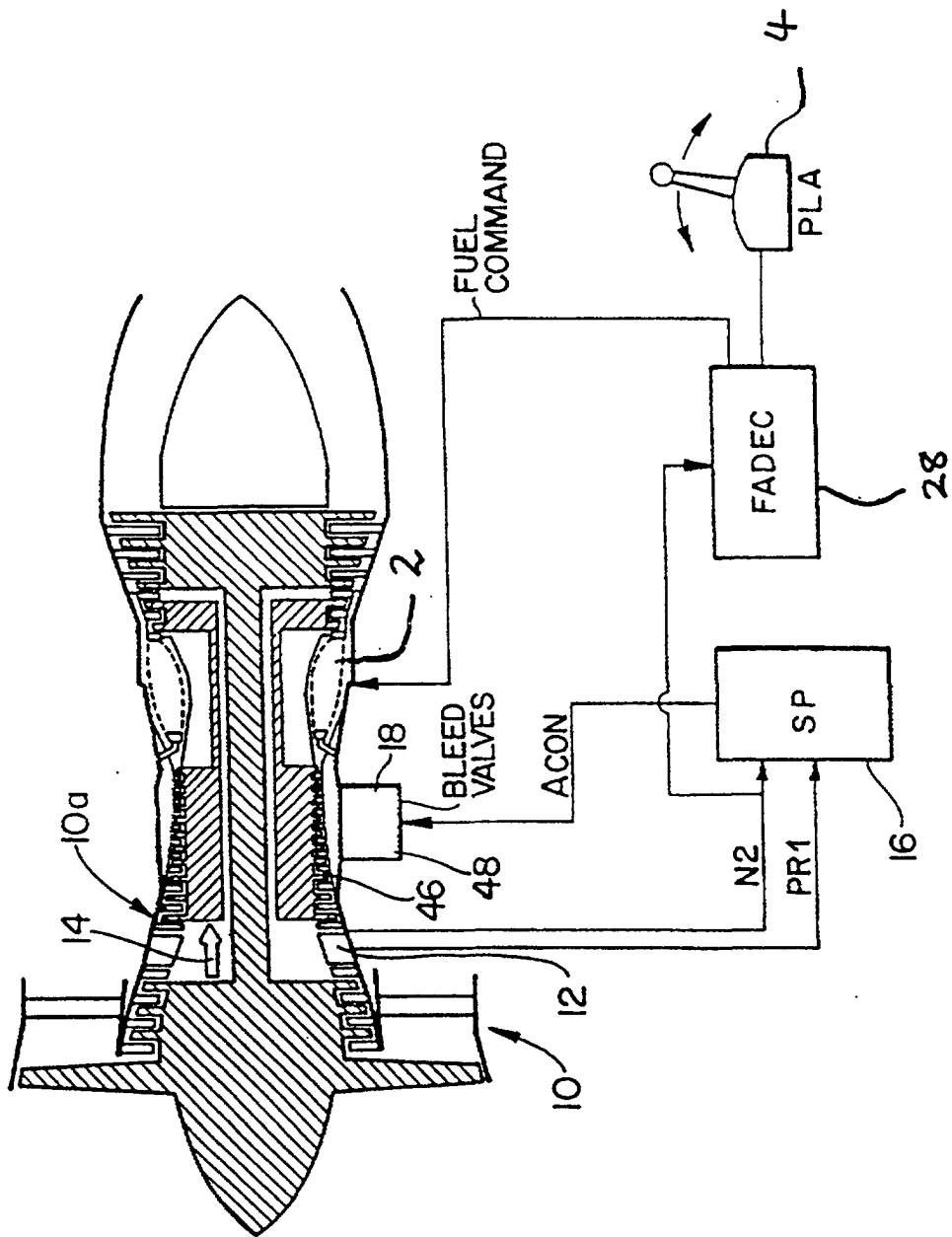
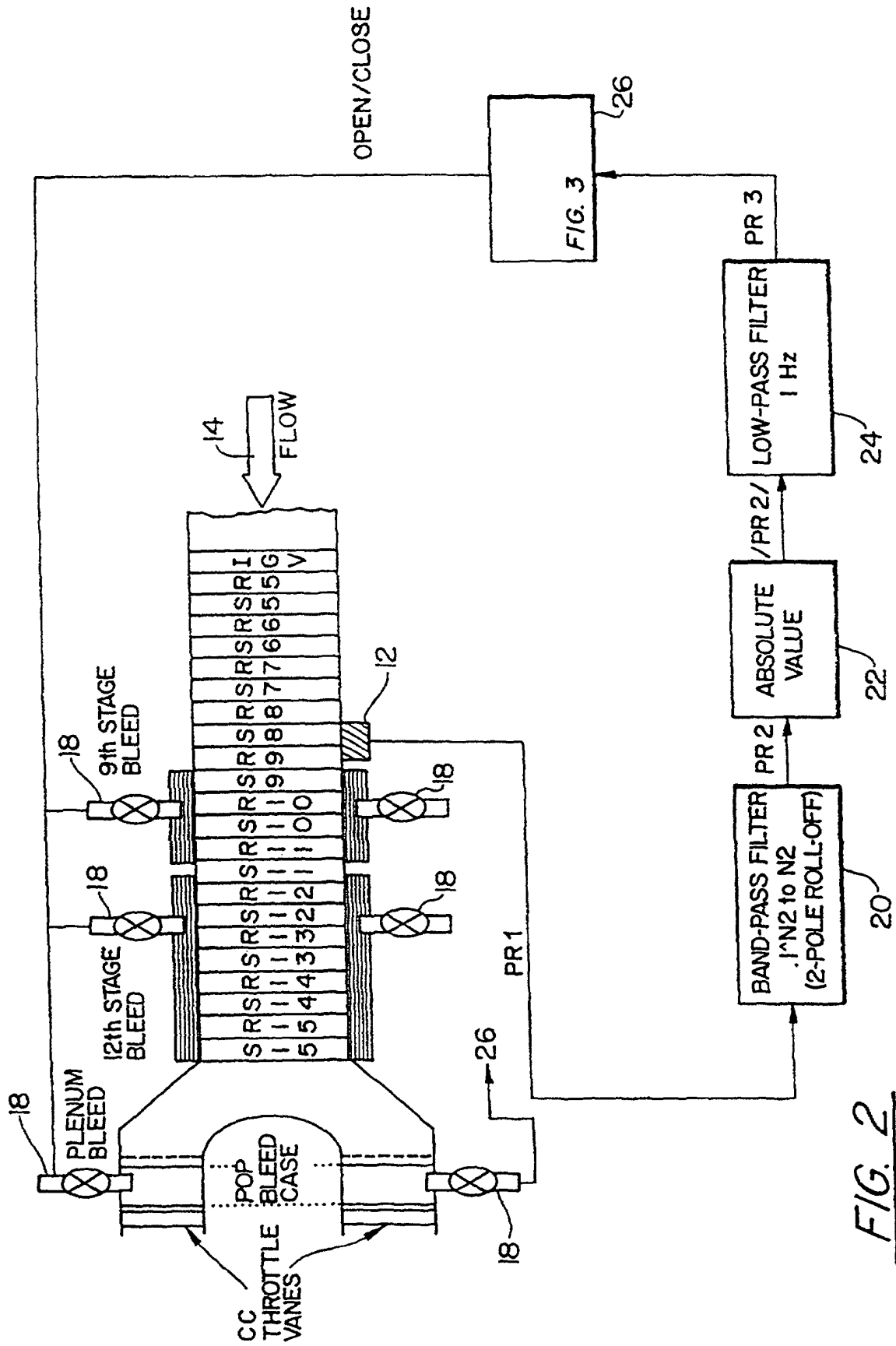


FIG. 1



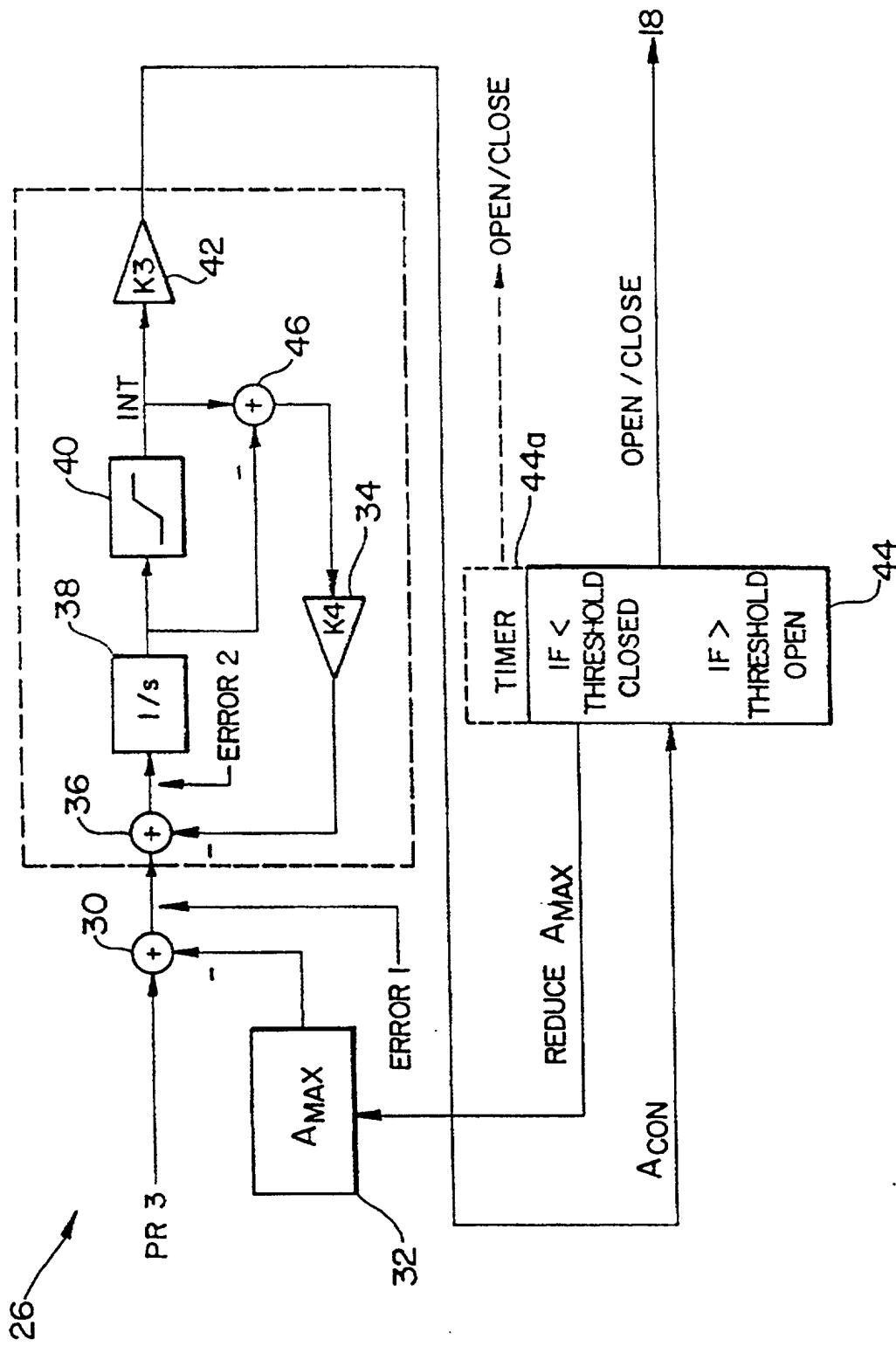


FIG. 3

FIG. 4

