

SPECIFICATION

Compressor surge control

5 DESCRIPTION

5

The invention relates to control systems for gas compressors for the avoidance of surge conditions, that is to say regulating the ratio of outlet to inlet pressure and the measured weight flow rate to prevent surge.

Gas compressor systems which supply, for example, air pressure to pneumatic loads are subject to an undesirable condition commonly referred to as surge. Although the reason for surge is not fully understood, its effect is extremely detrimental. For example, when a surge condition occurs in the compressor system, the airflow may suddenly reverse, cease or be interrupted. If the surge condition continues, the compressor can enter a deep surge condition causing damage to its internal components.

The invention provides a surge control system for a gas compressor comprising means for generating a first signal proportional to the ratio of the outlet pressure of the compressor to the inlet pressure of the compressor; means for establishing a second signal proportional to a reference value of this ratio; means for generating a third signal proportional to the weight flow rate of gas through the compressor; means for comparing the first signal plus the second signal to the third signal; means for generating a vent valve command signal if the resulting comparison is positive; and a vent valve position control circuit responsive to the vent valve command signal for opening and closing a vent valve which allows outlet gas to escape in an amount proportional to the vent valve command signal.

If the first signal plus the second signal exceeds the third signal, a surge condition may ensue, and the vent valve position command signal causes the vent valve to allow a portion of the gas to escape. Such venting reduces the output pressure from the compressor, lowers the pressure ratio and increases the weight flow rate. As the pressure ratio returns towards the reference pressure for the flow rate, the command signal begins to cause the valve to close, and operation along the operating line resumes.

During normal operation, the vent valve command signal is zero at all points along the operating line of the compressor surge map. This indicates that the reference pressure ratio plus the measured pressure ratio equals the weight flow rate. The weight flow rate of the air through the compressor may be adjusted to correct for pressure and temperature variations. Also, a transient control channel, responsive to the rate of change of the pressure ratio and/or weight flow rate, may be provided to fully vent the air if the rate of change of the pressure ratio and/or weight flow rate increases to a level indicating an ensuing surge condition. The effect of the reference pressure ratio is reduced to correspond to a lesser weight flow rate through the compressor which occurs as a result of decreasing the speed or repositioning the inlet guide vanes.

35 DRAWINGS

35

Figure 1 is a compressor surge map illustrating the application of the present invention;

Figure 2 is a block diagram of a surge control system according to the invention wherein a pressure differential Δp is measured at the outlet of the compressor; and

Figure 3 is a block diagram of a surge control system according to the invention wherein Δp is measured at the inlet of the compressor, and transient control is also provided.

Referring to Fig. 1, a surge map for a compressor is shown. The map shows a pressure ratio P_r plotted as a function of airflow rate W or corrected airflow rate, W' . P_r is the ratio of the outlet pressure, P_{out} , to the inlet pressure, P_{in} , and the corrected airflow rate W' (or W) is the weight of the air discharged from the compressor as a function of time (as for example lbs. per second).

Both P_r and W' are obtained by measuring various compressor parameters. P_{in} may be obtained by measuring the pressure at the inlet of the compressor by a pressure tube. P_{out} may be similarly measured by a pressure tube position at the outlet of the compressor. The pressures are converted to electrical signals which are manipulated to provide P_r . Airflow rate W' (and W) is proportional to a differential pressure measured at either the inlet or the outlet of the compressor. Hence, a differential pressure may be converted to an electrical signal and multiplied by a constant to provide W' .

The surge line on the map is acquired empirically by detecting and plotting values of P_r at which the compressor enters a surge condition for selected values of W' . The speed of the compressor and the position of its inlet guide vanes (IGV) affect the location of the operating position on the map, and movement on the map is along the common speed or common IGV line. For example, at a constant compressor speed, P_r increases with a decrease in airflow rate until the compressor reaches a surge condition, as can be seen by following the common speed line upwardly and to the left to the surge line as shown in Fig. 1. The magnitude of P_r for a given W' can be controlled by controlling the pressure at the outlet P_{out} for a particular flow rate. This may be accomplished by venting a portion of the air provided to the load. As the air is vented, P_{out} , and hence P_r , drops following the common speed line to the right and downwardly from the surge line to the operating line for the compressor. The compressor operating line is drawn in the normal operating region of the map and is selected to represent a displacement, as 5%, to the right of the surge line. It is desirable that the system maintain a pressure ratio P_r equal to or greater than the P_r value at the intersection of the operating line with the common speed line (or inlet guide vane position line) but less than the P_r value at the intersection of the surge line and the common speed line.

In the present invention, the pressure ratio P_r is controlled by a venting valve which increases or decreases

the output pressure P_{out} and weight flow rate W so that P_r equals the P_r value at the intersection of the common speed line with the operating line. The venting valve is controlled when the P_r value is in the surge correction region as shown in Fig. 1. The position of the valve determines the value of P_r and W and is controlled by a surge control circuit to be explained in greater detail below.

5 If the compressor is operating in surge condition (i.e., on the surge line), the valve is fully opened to most rapidly reduce P_r and increase W . If the compressor is operating in the normal operating region (i.e., on the operating line), the valve is fully closed. As the venting valve is opened, the pressure ratio P_r drops and the weight flow rate W increases along the common speed line (or along the common ICV line) toward the point of intersection with the normal operating line. As the pressure ratio approaches a value representing the
10 normal operating line, the surge control circuit of the present invention proportionally closes the valve and completely closes it when the pressure ratio P_r lies at the intersection of the operating line. Thereafter, if the pressure ratio increases to enter the surge correction region, the control valve is opened in an amount proportional to the magnitude of the correction required to drop the pressure ratio P_r back toward the intersection with the operating line.

15 An explanation of the operation of various control systems for the compressors will now be provided with particular reference to a centrifugal compressor having a backward curved impeller which has an extended choke to stall range and within that range an appreciable zone of constant pressure variable flow. Although the centrifugal compressor will be described in combination with the control circuits, it should be understood that the control circuits of the present invention are capable of controlling surge for any type of
20 compressor having a surge map similar to that shown in Fig. 1.

Referring to Fig. 2, a surge control system for a fixed speed, fixed geometry compressor is shown. A compressor 10 has an inlet 12 and an outlet 14 which supplies compressed air to pneumatic load 16 by a pneumatic conduit 18 which is coupled between the load 16 and the outlet 14. A venting conduit 20 is coupled in parallel with load 16 and has a dump valve 22 therein. The position of valve 22 determines the
25 amount of airflow from outlet 14 to a vent 24.

A pressure sensor 26, which may be a conventional transducer or a strain gauge, measures the pressure at inlet 12 and converts it to a signal representative of the amplitude of the pressure at that point. Similarly, a sensor 28 measures the pressure at outlet 14 and provides a signal P_{out} proportional to its magnitude. The signals representing P_{in} and P_{out} are applied to conditioning circuits 30 and 32, respectively. The conditioning
30 circuits remove noise and transients from the signals. The signals are then applied to a divider circuit 34 to divide the signal representing the outlet pressure P_{out} by a signal representing the input pressure P_{in} . The output from divider circuit 34, P_r , is applied to a summer 36 through an amplifier 38. The selection of the gain of amplifier 38 will be discussed in greater detail below.

The corrected weight flow W' can be expressed in the form of an equation as follows:

$$35 \quad W' = c \sqrt{\Delta p \left(\frac{P_{in}}{T_{in}} \right)} \quad (EQ 1)$$

40 where c is a selected airflow constant, Δp is the pressure difference at the outlet of the compressor, P_{in} is the inlet pressure, and T_{in} is the inlet temperature. Also, W' can be corrected for temperature and pressure by multiplying it by the $\frac{\sqrt{\theta}}{\delta}$ to equal $W' \frac{\sqrt{\theta}}{\delta}$ wherein θ is equal to $\frac{T_{in}}{519.7^\circ K}$ (EQ 2) and δ is $\frac{P_{in}}{14.7}$ (EQ. 3).

The multiplication of W' by the corrected values assures that a more accurate weight flow rate is obtained.

45 Returning to Fig. 2, a sensor 40, located in outlet 14, senses Δp . The Δp signal is provided to a Δp conditioning circuit 42 to remove noise. Also, temperature sensor 44 located at the inlet 12 senses the temperature and generates a signal proportional to it which is applied to temperature conditioning circuit 46. W' calculation circuit 48 receives the signals representing temperature, Δp and input pressure P_{in} from conditioning circuits 46, 42 and 30, respectively. The circuit manipulates C , Δp , P_{in} and T_{in} to provide an
50 output representing W' as in Equation 1, above.

Temperature and pressure correction of W' will now be considered. Temperature correction circuit 50 multiplies the signal received from temperature conditioning circuit 46 by an amount equal to that shown in Equation 2. The output from temperature correction circuit 50 is applied to a square root circuit 52 which obtains the square root of the value of the signal from the temperature correction circuit 50. The value from
55 the square root circuit 52 is multiplied by W' by multiplier 54. The product therefrom is provided to divide circuit 56. Also provided to divide circuit 56 is the signal representing δ from pressure correction circuit 58. The output from pressure correction circuit 58 is represented by Equation 3. The output from divide circuit 56 is applied to summer 36 through an amplifier 60. The selection of the gain of amplifier 60 will be discussed in greater detail below.

60 A signal representing $P_{r ref}$ is provided by $P_{r ref}$ circuit 37 and applied to summer 36. The signal from summer 36 is the sum of the signals from amplifier 60, amplifier 33 and $P_{r ref}$ circuit 37. The signal from summer 36 will be hereinafter referred to as the vent valve command signal and may be expressed in the form of an equation as

$$P_r + P_{r ref} - \frac{W' \sqrt{\theta}}{\delta} \quad (EQ 4)$$

The polarity of the signal is indicative of whether or not the system is operating in the surge correction region or in the normal operating region about a selected reference pressure P_r as shown in Fig. 1. That is to say, if the vent valve command signal is positive, the magnitude of the P_r term exceeds the magnitude of the W' term at a selected reference pressure P_r ref, and the operation of the compressor is operating in the surge correction region on the map in Fig. 1. If, however, the vent valve command signal is negative, the W' term is greater than the P_r term plus the P_r ref term, and the compressor is operating in the normal operating region of the map shown in Fig. 1. When P_r plus P_r ref equals the W' term, a zero output is provided from the summer which is an indication of the compressor operating on the operating line. The gains of amplifiers 38 and 60 are selected to balance the signals into summer 36 so that the output from summer 36 is zero everywhere on the selected operating line. In effect, this adjustment amounts to establishing the slope of the operating line.

The vent valve command signal from summer 36 controls the position of the valve 22. A negative signal indicates normal operation, as discussed above, and is removed by a negative clipper circuit 62. A positive signal passes through the negative clipper circuit 62 and is applied to a summer 64 through an amplifier 66. The gain of amplifier 66 is selected in accordance with the operating characteristics of the system. The positive voltage applied to summer 64 causes an output voltage to be provided to a valve position control circuit 68 through an amplifier 70. The position of the valve is related to the voltage applied to the valve position control circuit 68 in any convenient manner. For example, the positive voltage applied to the valve position control circuit 68 opens valve 22 in an amount proportional to the magnitude of the positive voltage. Zero volts causes valve 22 to be fully closed. A valve position demodulator circuit 72 provides feedback to summer 64 in a well known manner to assure that the valve position with respect to the applied voltage is maintained.

A variable speed or variable geometry compressor may be employed in lieu of fixed speed, fixed geometry compressor 10 discussed above. In such a situation, the calculated surge line must be shifted as required for a given inlet guide vane position or a selected speed. This may be most easily accomplished by adding a signal representative of the shift to summer 36 by an inlet guide vane or speed information circuit 74.

Referring to Fig. 3, another surge control circuit is shown. Circuits which are similar to that disclosed in Fig. 2 are similarly numbered. Also, an alternative method of acquiring the airflow rate and the P_r value will be described, it being understood that the circuitry described in Fig. 2 to provide such signals would be equally effective.

The input to summer 36 includes W , P_r and P_r ref. P_r and P_r ref are provided in a manner similar to that discussed above. W is obtained by a circuit 76 which multiplies Δp (taken at the inlet 12 rather than the outlet 14, as previously considered) by a constant. If Δp is acquired from the input, temperature and pressure factors are minimal, and in most cases correction circuitry need not be provided.

The valve position command signal from summer 36 is provided to negative clipper 62 for steady state control in a manner discussed above. Also, the valve command signal is applied in parallel to a positive clipper 78 which removes positive signals and passes negative signals which represent operation in the normal operating region. The surge command signal increases at a high rate as the pressure ratio P_r increases for a given weight flow rate W . A high rate of increase is a precursor to the surge condition. Thus, if

$$\frac{d(W - P_r)}{dt}$$

from a circuit 80 increases beyond a level established by a comparator/transfer function circuit 82, 82 provides a signal having a high gain to summer 64 through a circuit 84. The signal is of a sufficient magnitude to fully open valve 22 in a short period of time, as 15 μ seconds. The circuit then slowly returns to its original level after a long period of time, as 3 seconds, causing valve 22 to close. A higher signal controls circuit 84 and passes only the higher of the two input signals to effect transient and steady state control.

CLAIMS

1. A surge control system for a gas compressor comprising: means for generating a first signal proportional to the ratio of the outlet pressure of the compressor to the inlet pressure of the compressor; means for establishing a second signal proportional to a reference value of this ratio; means for generating a third signal proportional to the weight flow rate of gas through the compressor; means for comparing the first signal plus the second signal to the third signal; means for generating a vent valve command signal if the resulting comparison is positive; and a vent valve position control circuit responsive to the vent valve command signal for opening and closing a vent valve which allows outlet gas to escape in an amount proportional to the vent valve command signal.
2. A surge control system according to claim 1 in which the comparing means is a summer.
3. A surge control system according to claim 1 or claim 2 including means for multiplying the third signal and means for multiplying the first signal so that the vent valve command signal is zero along a selected compressor operating line for all values of weight flow rate.
4. A surge control system according to any preceding claim wherein the greater the magnitude of the valve command signal, the greater the amount of gas vented by the valve.
5. A surge control system according to any preceding claim wherein the generating means includes a



16

The polarity of the signal is indicative of whether or not the system is operating in the surge correction region or in the normal operating region about a selected reference pressure P_r as shown in Fig. 1. That is to say, if the vent valve command signal is positive, the magnitude of the P_r term exceeds the magnitude of the W' term at a selected reference pressure $P_{r \text{ ref}}$, and the operation of the compressor is operating in the surge correction region on the map in Fig. 1. If, however, the vent valve command signal is negative, the W' term is greater than the P_r term plus the $P_{r \text{ ref}}$ term, and the compressor is operating in the normal operating region of the map shown in Fig. 1. When P_r plus $P_{r \text{ ref}}$ equals the W' term, a zero output is provided from the summer which is an indication of the compressor operating on the operating line. The gains of amplifiers 38 and 60 are selected to balance the signals into summer 36 so that the output from summer 36 is zero everywhere on the selected operating line. In effect, this adjustment amounts to establishing the slope of the operating line.

The vent valve command signal from summer 36 controls the position of the valve 22. A negative signal indicates normal operation, as discussed above, and is removed by a negative clipper circuit 62. A positive signal passes through the negative clipper circuit 62 and is applied to a summer 64 through an amplifier 66. The gain of amplifier 66 is selected in accordance with the operating characteristics of the system. The positive voltage applied to summer 64 causes an output voltage to be provided to a valve position control circuit 68 through an amplifier 70. The position of the valve is related to the voltage applied to the valve position control circuit 68 in any convenient manner. For example, the positive voltage applied to the valve position control circuit 68 opens valve 22 in an amount proportional to the magnitude of the positive voltage. Zero volts causes valve 22 to be fully closed. A valve position demodulator circuit 72 provides feedback to summer 64 in a well known manner to assure that the valve position with respect to the applied voltage is maintained.

A variable speed or variable geometry compressor may be employed in lieu of fixed speed, fixed geometry compressor 10 discussed above. In such a situation, the calculated surge line must be shifted as required for a given inlet guide vane position or a selected speed. This may be most easily accomplished by adding a signal representative of the shift to summer 36 by an inlet guide vane or speed information circuit 74.

Referring to Fig. 3, another surge control circuit is shown. Circuits which are similar to that disclosed in Fig. 2 are similarly numbered. Also, an alternative method of acquiring the airflow rate and the P_r value will be described, it being understood that the circuitry described in Fig. 2 to provide such signals would be equally effective.

The input to summer 36 includes W , P_r and $P_{r \text{ ref}}$. P_r and $P_{r \text{ ref}}$ are provided in a manner similar to that discussed above. W is obtained by a circuit 76 which multiplies Δp (taken at the inlet 12 rather than the outlet 14, as previously considered) by a constant. If Δp is acquired from the input, temperature and pressure factors are minimal, and in most cases correction circuitry need not be provided.

The valve position command signal from summer 36 is provided to negative clipper 62 for steady state control in a manner discussed above. Also, the valve command signal is applied in parallel to a positive clipper 78 which removes positive signals and passes negative signals which represent operation in the normal operating region. The surge command signal increases at a high rate as the pressure ratio P_r increases for a given weight flow rate W . A high rate of increase is a precursor to the surge condition. Thus, if

$$\frac{d(W - P_r)}{dt}$$

from a circuit 80 increases beyond a level established by a comparator/transfer function circuit 82, 82 provides a signal having a high gain to summer 64 through a circuit 84. The signal is of a sufficient magnitude to fully open valve 22 in a short period of time, as 15μ seconds. The circuit then slowly returns to its original level after a long period of time, as 3 seconds, causing valve 22 to close. A higher signal controls circuit 84 and passes only the higher of the two input signals to effect transient and steady state control.

CLAIMS

1. A surge control system for a gas compressor comprising: means for generating a first signal proportional to the ratio of the outlet pressure of the compressor to the inlet pressure of the compressor; means for establishing a second signal proportional to a reference value of this ratio; means for generating a third signal proportional to the weight flow rate of gas through the compressor; means for comparing the first signal plus the second signal to the third signal; means for generating a vent valve command signal if the resulting comparison is positive; and a vent valve position control circuit responsive to the vent valve command signal for opening and closing a vent valve which allows outlet gas to escape in an amount proportional to the vent valve command signal.
2. A surge control system according to claim 1 in which the comparing means is a summer.
3. A surge control system according to claim 1 or claim 2 including means for multiplying the third signal and means for multiplying the first signal so that the vent valve command signal is zero along a selected compressor operating line for all values of weight flow rate.
4. A surge control system according to any preceding claim wherein the greater the magnitude of the valve command signal, the greater the amount of gas vented by the valve.
5. A surge control system according to any preceding claim wherein the generating means includes a

17



clipper circuit for passing the command signal of a polarity indicative of the first signal plus the second signal exceeding the third signal.

6. A surge control system according to any preceding claim including means for differentiating the vent valve command signal with respect to time to provide a differential signal, means for comparing the differential signal with a differential reference signal, and means for generating a signal to cause the valve to open if the differential signal exceeds the differential reference signal.

7. A surge control system according to claim 6 including a clipper circuit coupled between the comparing means for the first, second and third signals and the differentiating means for passing the vent valve command signal of a polarity indicative of the weight flow rate signal exceeding the first signal plus the second signal and inhibiting the vent valve command signal of a polarity indicative of the first signal plus the second signal exceeding the third signal.

8. A surge control system according to claim 6 or claim 7 wherein the means for generating a signal to cause the valve to open if the differential signal exceeds the differential reference signal also generates a signal to cause the valve to close after a selected time.

9. A surge control system according to any preceding claim wherein the means for generating the first signal includes means for providing a signal representative of inlet pressure; means for providing a signal representative of outlet pressure; and means for dividing them.

10. A surge control system according to any preceding claim wherein said means for generating the third signal includes means for generating a signal representative of a pressure difference Δp at the outlet of the compressor; means for generating a signal proportional to the temperature at the inlet of the compressor; means for generating a signal $W' \times c \left(\frac{P_{in}}{T_{in}} \right)$ wherein c is a

constant, P_{in} is the inlet pressure and T_{in} is the inlet temperature; means for dividing T_{in} by 519.7 to provide a temperature correction factor θ ; means for providing $\sqrt{\theta}$; means for dividing P_{in} by 14.7 to provide a pressure correction factor δ ; means for multiplying W' by $\sqrt{\theta}$ to provide $W' \sqrt{\theta}$ and means for dividing $W' \sqrt{\theta}$ by δ to provide $\frac{W' \sqrt{\theta}}{\delta}$.

11. A surge control system according to any of claims 1 to 9 wherein the means for generating the third signal includes means for generating a signal representative of a pressure difference Δp at the inlet of the compressor and means for multiplying the signal representative of a pressure difference Δp at the inlet by a constant to provide a signal proportional to the actual weight flow rate.

12. A surge control system as herein described with reference to Figure 2 of the drawings.

13. A surge control system as herein described with reference to Figure 3 of the drawings.