

SPECIFICATION

Compressor surge control

5 DESCRIPTION

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

10 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.

15 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 generating a second signal corresponding to a selected reference value of this ratio; means for comparing the first signal with the second signal and providing a vent valve command signal; and vent valve position control means 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.

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 for a fixed speed, fixed geometry compressor according to the invention;

40 *Figure 3* is a block diagram of a surge control system for a variable speed, fixed geometry compressor according to the invention;

Figure 4 is a block diagram of a surge control system for a fixed speed, variable geometry compressor according to the invention; and

45 *Figure 5* is a block diagram of a surge control system for a variable speed, variable geometry compressor according to the invention.

Referring to *Figure 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 . P_r is the ratio of the outlet pressure P_{out} to the inlet pressure P_{in} . Airflow rate W is the weight of the air discharged from the compressor as the function of time (as, for example, lbs. per second). The airflow rate may also be corrected for temperature and pressure variations, in which case the value is denoted by W' .

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 positioned at the outlet of the compressor. The pressures are converted to electrical signals which are manipulated to provide

65 P_r , W or W' are proportional to a differential pres-

sure measured at the input of the compressor. Hence, the differential pressure at the input is converted to an electrical signal and multiplied by a constant to provide W or W' .

70 The surge line on the map is acquired empirically by detecting a 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 without an increase in airflow rate until the compressor reaches the surge condition, as can be seen by following a common speed line upwardly to the surge line, as shown in *Figure 1*.

The magnitude of P_r for a given W can be controlled by controlling P_{out} for a particular airflow rate.

85 This may be accomplished by venting a portion of the air provided to the load. As air is vented, P_{out} , and hence P_r , drops, following the common speed line downwardly from the surge line. 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 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 P_{out} so that P_r equals the P_r value at the intersection of the common speed line with the operating line. The valve is opened or closed when the P_r value is in the surge correction region, as shown in *Figure 1*. The position of the valve determines the value of P_r and is controlled by a surge control circuit to be explained in greater detail below.

If the compressor is operating in surge condition (on the surge line), the valve is fully opened. If the compressor is operating in the normal operating region (on the operating line) the valve is fully closed. Proportional control of the valve position occurs when P_r is in the surge correction region. As the valve is opened, the pressure ratio P_r drops along the common speed line toward the point of intersection with the normal operating line. As the pressure ratio approaches the normal operating line, the control valve 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 system of the present invention opens a valve in an amount proportional to the magnitude of the correction required to drop the pressure back toward the operating line.

An explanation of the operation of various control systems for the compressors will now be provided with particular reference to an axial compressor. Although an axial compressor will be described in

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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 compressor having a surge map similar to that shown in Figure 1.

Referring to Figure 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 loads 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 which determines the amount of air vented by vent 24. A pressure sensor 26, which may be a conventional or strain gauge transducer, measures the pressure at the inlet 12 and converts it to a signal P_{in} representative of the magnitude of the pressure. Similarly, a sensor 28 measures the pressure at outlet 14 and generates 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 circuits remove noise and transients from the signals. The signals are then applied to a divider circuit 34 which divides the P_{out} signal by the P_{in} signal to provide output signal P_r . The output from divider circuit 34 is applied to a summer 36 where it is summed with a signal from P_r reference circuit 38. The level of the signal from the P_r reference circuit 38 is set equal to the desired pressure ratio P_r ref. at the intersection of the common speed line representing maximum flow rate W and the operating line (Figure 1).

The output of summer 36 is referred to as the vent valve position command signal and is negative when the compressor is operating in the normal operating region since the value from P_r reference circuit is greater than the value from divider circuit 34. If the pressure ratio P_r (which follows a common speed or IGV line) exceeds the selected P_r ref., the valve position command signal from summer 36 is positive. This position on the surge map of Figure 1 is located in the surge correction region and is indicative of an ensuing surge condition. When P_r is in this section of the surge map, valve 22 must be opened to reduce P_r so that a surge condition does not occur. The magnitude and the polarity of the valve position command signal controls the position of valve 22, as will be explained in greater detail below.

The valve position command signal is applied to a summer 39 through an amplifier 40. The gain of amplifier 40 is selected in accordance with the operating characteristics of the system. A voltage applied to a summer 39 causes an output voltage to be provided to a valve position control circuit 42 through an amplifier 44. The position of the valve is related to the voltage applied to valve position control circuit 42 in any convenient manner. For example, a positive voltage applied to the valve position control circuit 42 may be used to open valve 22 in an amount proportional to the magnitude, whereas zero volts, or negative voltage, causes valve 22 to be fully closed.

Valve position demodulator circuit 46 provides negative feedback to summer 39 to assure that the valve position with respect to the applied voltage is maintained. If P_r increases and enters the surge control region on the map of Figure 1, the valve position command signal is positive and causes valve 22 to open. When valve 22 opens, P_r decreases, which in turn decreases the magnitude of the valve position command signal causing valve 22 to close. When the valve position command signal decreases to zero or becomes negative the valve 22 is fully closed and the compressor is operating in the normal operating region.

Referring to Figure 3, a surge control system for a variable speed, fixed geometry compressor 48 is provided. The system shown in Figure 3 is similar to the system shown for the fixed speed, fixed geometry system of Figure 2. The difference between the two systems is easily seen in that valve position command signal from summer 36 is modified by a signal representing various compressor speeds. Specifically, as the speed of the compressor is selectively decreased to a percentage of full speed, the value of P_r on the operating line also decreases. Five different speeds are shown in Figure 1, and each represents a selected percentage of full speed.

The speed of compressor 48 is sensed by a sensor 50 to provide a signal proportional to the actual speed. A speed demodulator circuit 52 converts the signal representing the actual speed to a proportional voltage. A describing function 54 provides an output to summer 36 through an amplifier 56. The gain of amplifier 56 is selected in accordance with the operating parameters of the system. As the various speeds are selected in decreasing magnitude, the output of the describing function 54 increases. The relationship between the input and the output is usually linear, although a describing function other than linear may be used if desired. The describing function may also modify the input signal for altitude, temperature or pressure.

The valve position command signal from summer 36 is similar to that discussed above with respect to the fixed speed, fixed geometry compressor (Figure 2), except that its magnitude is proportional to a reduced value of P_r indicative of a reduction in the selected speed. Thus, for the five common speeds shown in Figure 1, the describing function 54 and amplifier 56 provide five individual voltage levels, each of which reduces the effect of P_r ref. so that the signals generated by the circuit correspond to the P_r at the intersection of the operating line with the selected common speed line. The valve position command signal from summer 36 controls the position of valve 22 in a manner similar to that discussed above.

Referring to Figure 4, a surge control system for a fixed speed, variable geometry compressor 58 is shown. For the purpose of this invention, the term 'variable geometry compressor' means a compressor having positionable inlet guide vanes which control the weight flow rate through the compressor. The surge control system shown in Figure 4 is similar to the system shown for the fixed

speed system in Figure 2. The difference between the two systems is easily seen in that the valve position command signal from summer 36 is modified by a signal representing the various inlet guide vane positions of the compressor. Specifically, as the inlet guide vanes (IGV) are positioned in an angular relationship with respect to the position representing maximum weight flow W , the value of P_r along the operating line decreases in a manner similar to the effect of a reduction in compressor speed. Five different inlet guide vane positions are shown in Figure 1, and each represents a selected angular relationship with respect to the position representing maximum weight flow W . The IGV position is sensed by a sensor 60 to provide a signal proportional to the actual position of the inlet guide vanes. An IGV position demodulator 62 converts the signal representing the IGV position to a proportional voltage. Describing function 64 provides an output to summer 36 through an amplifier 66. The gain of amplifier 66 is selected in accordance with the operating parameters of the system. As the inlet guide vanes are positioned to decrease the magnitude of the weight flow rate, the output from the describing function 64 increases.

The valve position command signal from summer 36 is similar to that discussed above with respect to Figure 2, except that its magnitude is reduced by an amount proportional to the P_r drop indicative of a lower weight flow rate W due to the selection of a particular inlet guide vane position. Thus, for the five IGV lines shown in Figure 1, the describing function 64 and amplifier 66 provide five individual voltage levels, each of which has the effect of reducing P_r ref. so that the circuit provides a signal representative of the pressure ratio having a value equal to the value of P_r at the intersection of the operating line with the IGV line.

The operation of the variable speed, variable geometry compressor will now be considered. However, before the details of the surge control system for the variable speed, variable IGV system are provided, it is helpful to consider the nature of the surge control map for such a compressor. If both the speed and the geometry of the compressor are permitted to be controlled, the surge mapping function becomes three-dimensional. Specifically, individual maps, each of which represent a common speed and each of which is similar to that shown in Figure 1 are provided for each inlet guide vane position. Thus, the particular value of P_r for a selected flow rate W is determined not only by the speed of the compressor, but also by the inlet guide vane position. Since both the inlet guide vane position and the speed of the compressor affect the position of P_r on an operating line for a particular flow rate, signals representing both these parameters must be added to the signal representing P_r ref. having the effect of reducing P_r ref. to accommodate the selected comparison speed and the selected inlet guide vane position.

Referring to Figure 5, the system for controlling surge in the variable speed, variable geometry compressor 68 is shown. The system is similar to that shown in Figure 2 except that a signal repre-

senting compressor speed (similar to that provided by the system shown in Figure 3) and a signal representing inlet guide vane position (similar to that shown by the circuit of Figure 4) are applied to summer 36. The valve position command signal from summer 36 is provided in a manner similar to that discussed above, but is reduced by an amount proportional to the pressure ratio drop due to the particular position of the inlet guide vanes and the selected speed of the compressor.

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 generating a second signal corresponding to a selected reference value of this ratio; means for comparing the first signal with the second signal and providing a vent valve command signal; and vent valve position control means responsive to the 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 wherein the vent valve command signal is of one polarity when the first signal is greater than the second signal and of the opposite polarity when the second signal is greater than the first signal.

3. A surge control system according to claim 2 wherein the vent valve position control means is responsive only to a valve command signal of a polarity indicative of the first signal being greater than the second signal.

4. A surge control system according to any preceding claim wherein the means for generating the first signal includes: means for providing a signal proportional to outlet pressure; means for providing a signal proportional to inlet pressure; and means for dividing these signals.

5. A surge control system according to any preceding claim wherein the comparing means is a summer.

6. A surge control system according to any preceding claim wherein the vent valve position control means includes: a summer for receiving the vent valve command signal; a valve position control circuit for positioning the valve coupled to the output of the summer; and a valve position demodulator for providing a signal to the summer indicative of the position of the valve.

7. A surge control system according to any preceding claim for a variable speed compressor comprising means for providing further signals to the comparing means, which signals are representative of a decrease in pressure ratio due to a decrease in compressor speed and decrease the effect of the signal corresponding to the maximum selected speed of the compressor at the comparing means.

8. A surge control system according to any of claims 1 to 6 for a variable geometry compressor comprising means for providing further signals to the comparing means, which signals are representative of inlet guide vane positions correspond-



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speed system in Figure 2. The difference between the two systems is easily seen in that the valve position command signal from summer 36 is modified by a signal representing the various inlet guide

- 5 vane positions of the compressor. Specifically, as the inlet guide vanes (IGV) are positioned in an angular relationship with respect to the position representing maximum weight flow W , the value of P_r along the operating line decreases in a manner
- 10 similar to the effect of a reduction in compressor speed. Five different inlet guide vane positions are shown in Figure 1, and each represents a selected angular relationship with respect to the position representing maximum weight flow W . The IGV
- 15 position is sensed by a sensor 60 to provide a signal proportional to the actual position of the inlet guide vanes. An IGV position demodulator 62 converts the signal representing the IGV position to a proportional voltage. Describing function 64 provides an
- 20 output to summer 36 through an amplifier 66. The gain of amplifier 66 is selected in accordance with the operating parameters of the system. As the inlet guide vanes are positioned to decrease the magnitude of the weight flow rate, the output from the
- 25 describing function 64 increases.

The valve position command signal from summer 36 is similar to that discussed above with respect to Figure 2, except that its magnitude is reduced by an amount proportional to the P_r drop indicative of a

30 lower weight flow rate W due to the selection of a particular inlet guide vane position. Thus, for the five IGV lines shown in Figure 1, the describing function 64 and amplifier 66 provide five individual voltage levels, each of which has the effect of reducing P_r ref. so that the circuit provides a signal representative of the pressure ratio having a value equal to the value of P_r at the intersection of the operating line with the IGV line.

The operation of the variable speed, variable

40 geometry compressor will now be considered. However, before the details of the surge control system for the variable speed, variable IGV system are provided, it is helpful to consider the nature of the surge control map for such a compressor. If both

- 45 the speed and the geometry of the compressor are permitted to be controlled, the surge mapping function becomes three-dimensional. Specifically, individual maps, each of which represent a common speed and each of which is similar to that shown in
- 50 Figure 1 are provided for each inlet guide vane position. Thus, the particular value of P_r for a selected flow rate W is determined not only by the speed of the compressor, but also by the inlet guide vane position. Since both the inlet guide vane position
- 55 and the speed of the compressor affect the position of P_r on an operating line for a particular flow rate, signals representing both these parameters must be added to the signal representing P_r ref. having the effect of reducing P_r ref. to accommodate the
- 60 selected comparison speed and the selected inlet guide vane position.

Referring to Figure 5, the system for controlling surge in the variable speed, variable geometry compressor 68 is shown. The system is similar to

- 65 that shown in Figure 2 except that a signal repre-

sents compressor speed (similar to that provided by the system shown in Figure 3) and a signal representing inlet guide vane position (similar to that shown by the circuit of Figure 4) are applied to summer 36. The valve position command signal from summer 36 is provided in a manner similar to that discussed above, but is reduced by an amount proportional to the pressure ratio drop due to the particular position of the inlet guide vanes and the selected speed of the compressor.

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 generating a second signal corresponding to a selected reference value of this ratio; means for comparing the first signal with the second signal and providing a vent valve command signal; and vent valve position control means responsive to the 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 wherein the vent valve command signal is of one polarity when the first signal is greater than the second signal and of the opposite polarity when the second signal is greater than the first signal.
3. A surge control system according to claim 2 wherein the vent valve position control means is responsive only to a valve command signal of a polarity indicative of the first signal being greater than the second signal.
4. A surge control system according to any preceding claim wherein the means for generating the first signal includes: means for providing a signal proportional to outlet pressure; means for providing a signal proportional to inlet pressure; and means for dividing these signals.
5. A surge control system according to any preceding claim wherein the comparing means is a summer.
6. A surge control system according to any preceding claim wherein the vent valve position control means includes: a summer for receiving the vent valve command signal; a valve position control circuit for positioning the valve coupled to the output of the summer; and a valve position demodulator for providing a signal to the summer indicative of the position of the valve.
7. A surge control system according to any preceding claim for a variable speed compressor comprising means for providing further signals to the comparing means, which signals are representative of a decrease in pressure ratio due to a decrease in compressor speed and decrease the effect of the signal corresponding to the maximum selected speed of the compressor at the comparing means.
8. A surge control system according to any of claims 1 to 6 for a variable geometry compressor comprising means for providing further signals to the comparing means, which signals are representative of inlet guide vane positions correspond-

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ing to a decrease in weight flow rate through the compressor and decrease the effect of the signal corresponding to the inlet guide vane position at the comparing means.

- 5 9. A surge control system according to any of claims 1 to 6 for a variable speed, variable geometry compressor comprising means for providing third signals to the comparing means, which third signals are representative of inlet guide vane positions corresponding to a decrease in weight flow rate through the compressor and decrease the effect of the signal corresponding to the maximum selected speed of the compressor and the inlet guide vane position at the comparing means, and means for
- 10 providing fourth signals to the comparing means, which fourth signals are representative of a decrease in pressure ratio due to a decrease in compressor speed and decrease the effect of the signal corresponding to the maximum selected speed of the
- 15 compressor and the inlet guide vane position at the comparing means.
- 20 10. A surge control system for a compressor as herein described with reference to Figure 2 of the drawings.
- 25 11. A surge control system for a compressor as herein described with reference to Figure 3 of the drawings.
- 30 12. A control system for a compressor as herein described with reference to Figure 4 of the drawings.
13. A surge control system for a compressor as herein described with reference to Figure 5 of the drawings.