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Elimination of Instability in Modulating Capacity Reciprocating Compressor

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ELIMINATION OF INSTABILITY IN MODULATING CAPACITY RECIPROCATING COMPRESSOR

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ABSTRACT

A reciprocating compressor which utilizes a rotating eccentric to modulate capacity by activating or deactivating a cylinder was developed. Several conditions were identified during development which would lead to unstable operation and possible part failure. These conditions mainly consisted of pressure forces acting upon the piston to push the rotating eccentric away from the stops on the crankshaft. A novel solution requiring no additional mechanisms was found. This solution utilized an offset center of gravity which would create a centrifugal force to counteract the separation forces. The centrifugal force along with a reduction in the pressure forces eliminated the instability problems.

BACKGROUND

There are many benefits to capacity modulation such as improved creature comforts and increased system efficiency. The major obstacle to capacity modulation has been the high cost of these systems. A modulating capacity reciprocating compressor was developed to provide capacity modulation at much lower applied cost than prior technology.

This reciprocating compressor provides full load capacity when the crankshaft is rotated in one direction and part load when rotated in the reverse direction. A rotate-able eccentric that is driven by stops on the crankshaft provides the means of disengaging one cylinder. Figure 1 shows the mechanism engaged in one cylinder mode (no stroke on switchable cylinder) and Figure 2 shows the two cylinder mode (full stroke). Figure 3 shows the crankshaft rotating and switching modes.

With such a crankshaft/eccentric arrangement, there are forces that can act on the mechanism to cause separation of the eccentric from its stop during compressor operation. These forces are a result of the pressure differential across the piston at certain crank angles. Once these forces dissipate or are overcome, the crankshaft stop will catch up to and collide with the eccentric stop causing noise and high impact stresses. Previous work done on this type mechanism had identified the existence of these phenomenon but no solutions were developed. This paper will summarize the instability problems encountered and discuss the solutions developed.

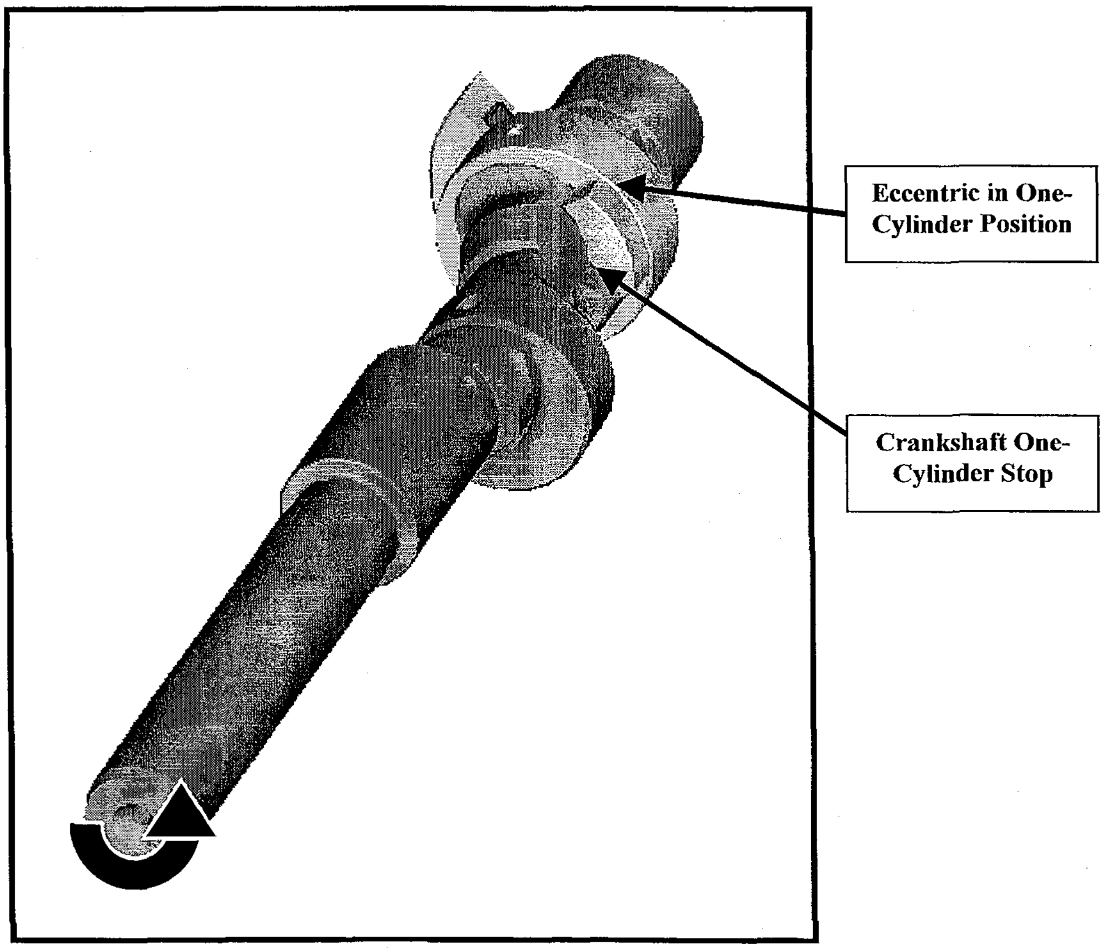

Figure 1

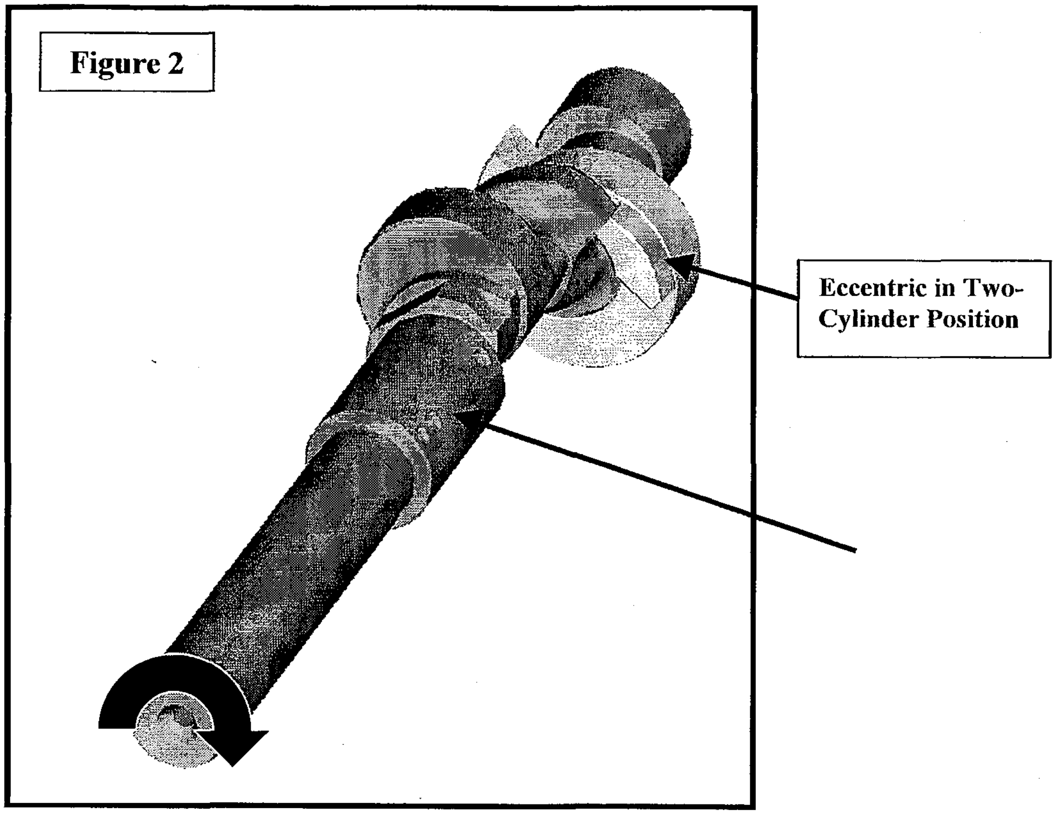

Figure 2

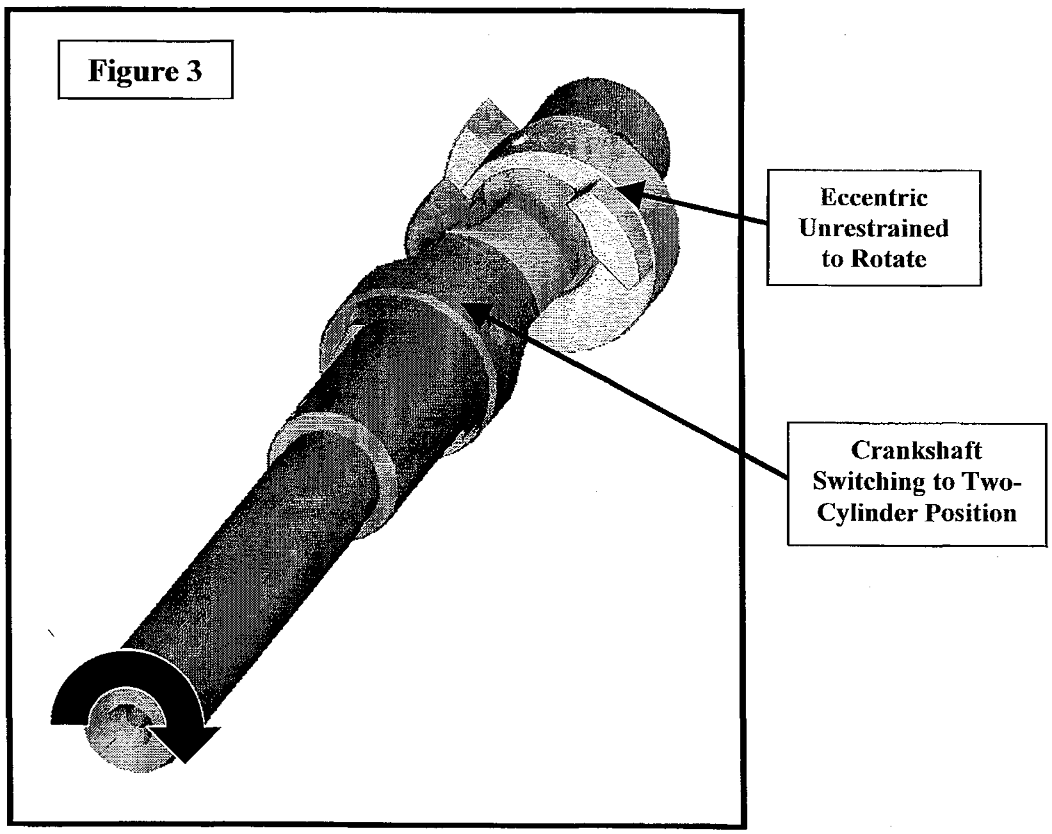

Figure 3

SUMMARY OF INSTABILITY MODES

There are a number of cases where the mechanism can become unstable and separation of the stops occurs. In each case, the net pressure force acting on the piston through the connecting rod has a magnitude and direction such that the eccentric stop is forced away from the crankshaft stop. A summary of these modes is as follows:

- One cylinder mode (switchable cylinder deactivated) with leaking discharge pressure

If incidental high pressure (i.e. pressure greater than the low pressure side of the compressor) leaks past the discharge valve of the deactivated cylinder, the high pressure in the cylinder ($P_1 > P_L$) will tend to push the eccentric from the stop at some crank angles shown in Figure 4.

- One cylinder mode (switchable cylinder deactivated) start-up

During one cylinder mode, the switchable piston is stationary at mid-stroke while the crankshaft rotates. If the piston is below mid-stroke at one cylinder mode start-up, the gas existing in the cylinder will be compressed to a higher pressure ($P_C > P_L$) when the piston moves to its stationary mid-stroke position. Similar to the previous mode as shown in Figure 4, the high pressure in the cylinder could potentially separate the stops.

- Two cylinder mode with high discharge pressure immediately after top dead center (TDC)

During two cylinder mode, as the piston passes TDC, the high pressure gas left in the cylinder after the discharge valve closes can potentially push the eccentric away from the crankshaft stop as shown in Figure 5 ($P_C > P_L$). This instability mode proved to be the most challenging to overcome.

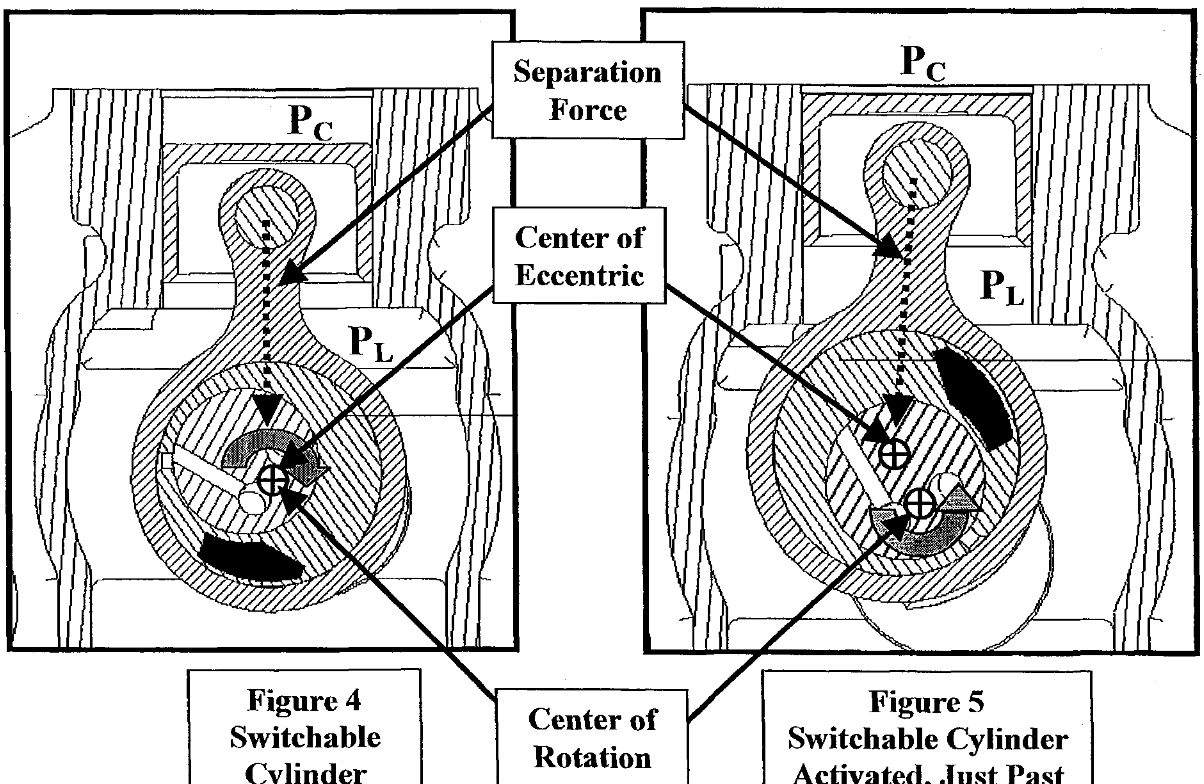

Figure 4 Switchable Cylinder Deactivated

Figure 5 Switchable Cylinder Activated, Just Past TDC

- Two cylinder mode with low cylinder pressure immediately after bottom dead center (BDC)

During two cylinder mode, the pressure in the switchable cylinder can be lower than the ambient pressure in the compressor just after the piston moves through BDC at the end of the suction stroke. In this scenario, as shown in Figure 6, the high ambient pressure can potentially push the eccentric away from the crankshaft stop ($P_L > P_C$).

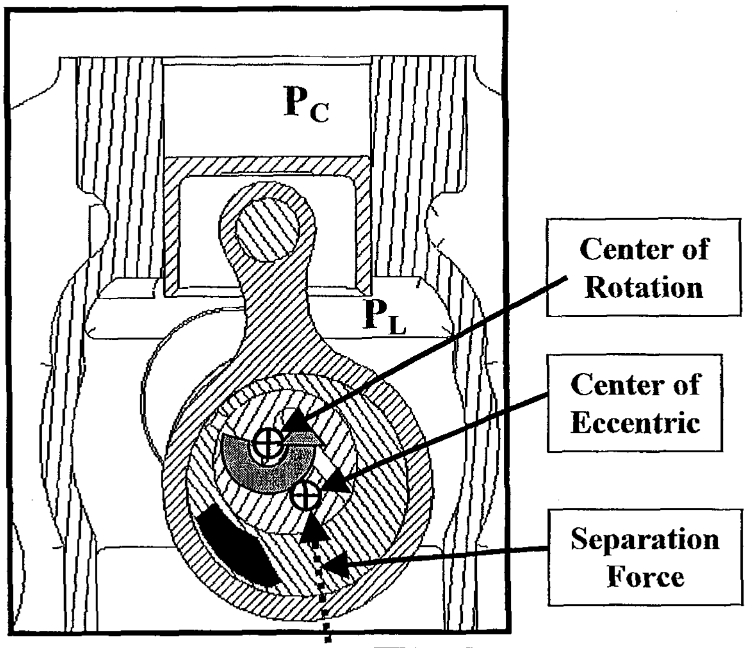

Figure 6
Switchable Cylinder Activated, Just After BDC

PROBLEMS ASSOCIATED WITH INSTABILITY

The separation of the stops on the rotating eccentric and crankshaft create many subsequent problems. The first and most obvious problem is the noise, or chatter, created. The separations can occur many times during a single revolution creating a noticeable chatter. At low pressure differentials, the chatter can be merely a nuisance while not jeopardizing the compressor operation. At medium pressure differentials, the separation distance becomes larger to the point that performance suffers. At high pressure differentials, the separation distance becomes enough to allow the rotating eccentric to rotate 180° to the other operating mode. The impact stress created by the collisions can also lead to part failure.

SOLUTIONS TO INSTABILITY MODES

Several solutions to the instability problems were evaluated. Most involved the use of a catch that would physically hold the stops together. The problem with most of these designs was that the holding force necessary to keep the stops together during operation would also hold the stops together during reversal of the motor. Thus the eccentric was not able to rotate and switch the piston from active to inactive operation or vice versa.

The instability mode found to be most challenging was the one developed during two cylinder mode just past top dead center. The separation forces developed here were basically the result of the high pressure gas left in the clearance volume at top dead center. The separation force depends not only on the pressure but also the moment arm and the moment arm increases as the crankshaft rotates further away from top dead center. The speed (and amount of crankshaft rotation) at which the pressure decreases depends greatly on the size of the clearance volume. The larger the clearance volume, the longer it takes for the pressure to decrease to an acceptable level, and the larger the moment arm becomes. Because of this, the clearance volume on the switchable cylinder was minimized. This reduces, but does not eliminate the instability.

A more promising solution to the instability involved using centrifugal force created by the rotating eccentric to counter act the forces created by the pressure differentials. The center of gravity of the rotating eccentric can be positioned in such a way as shown in Figure 7 so that a moment will be created about the crankshaft eccentric when the compressor is operating. The location of the center of gravity and the weight of the rotating eccentric were optimized in regards to certain size and space restraints to give the highest counteracting centrifugal force possible. This force along with the minimized clearance volume was enough to counteract the separation forces developed under the highest of compression ratios. This solution worked well for the instability modes associated with two cylinder operation but not with single cylinder operation. This was due to the centrifugal force being greatly diminished in one cylinder mode because the Cg of the eccentric is much closer to the centerline of the crankshaft shaft.

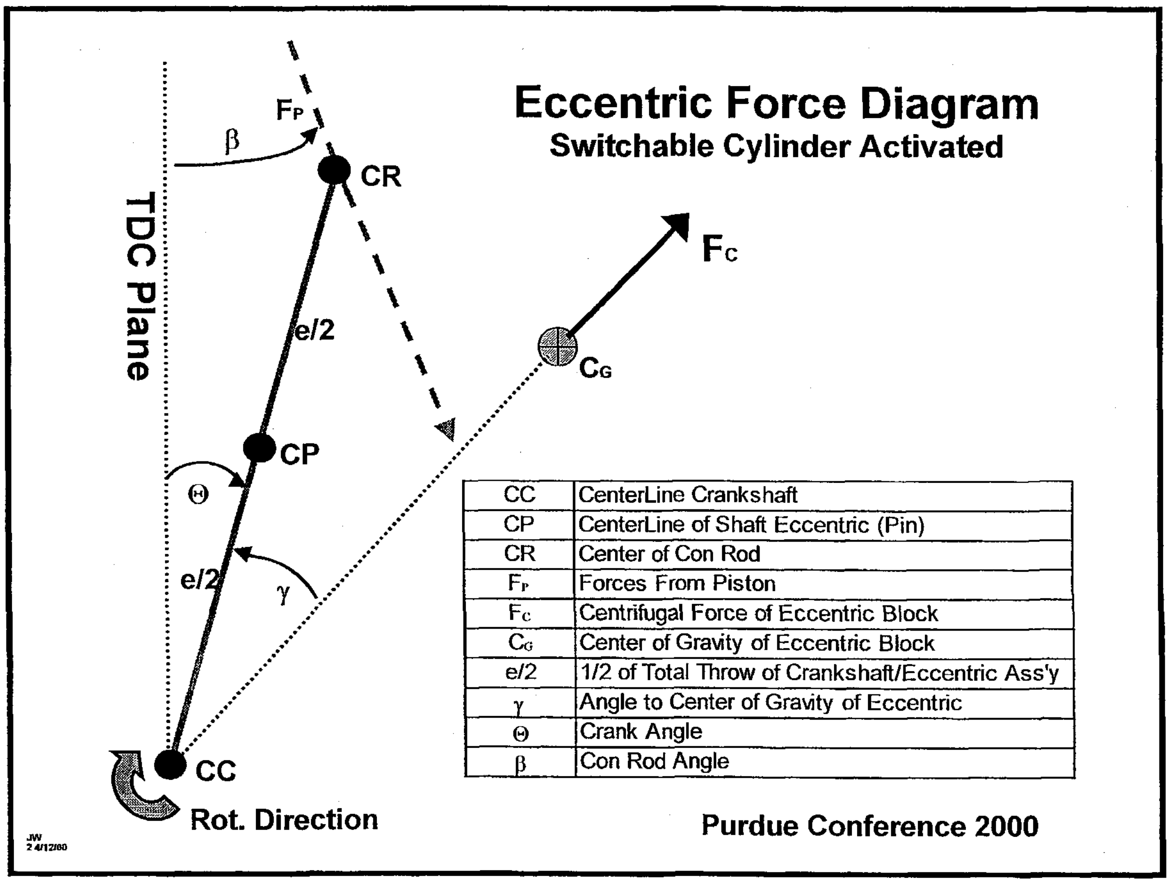

Figure 7

In the case of the instability modes during single cylinder operation, it was found that eliminating the increase in pressure due to leaking discharge valves and start-up compression was the best solution. To accomplish this, a vent hole was put in the switchable cylinder to allow the pressure in the cylinder to equalize with the ambient pressure inside the compressor housing (Allow $P_C=P_L$ while switchable cylinder is deactivated). The vent hole was positioned at the top edge of the piston at its mid-stroke location thus allowing pressure equalization during the inactive mode. During active mode the vent hole is covered by the piston during the last half of the compression stroke. The vent hole diameter was optimized to give adequate pressure equalization response while minimizing the amount of leakage during the first half of the compression stroke.

RESULTS

The minimized clearance volume, optimized centrifugal force and vent hole solutions were all implemented. The compressors assembled with these solutions were subjected to various testing conditions and the instability problems were eliminated.

The additional eccentric weight was also found to improve the switching characteristics from one cylinder mode to two cylinder mode. The sensitivity to factors such as fit and contamination was greatly reduced by the additional weight added to the rotating eccentric.

CONCLUSIONS

A crankshaft with a rotating eccentric used to activate or deactivate a cylinder of a reciprocating compressor was developed to provide cost effective capacity modulation. The basic action of this rotating eccentric is relatively straight forward, however there were several conditions found during development which lead to instability of the rotating eccentric. These instability problems were identified and novel solutions were found and implemented. The solutions implemented include the use of an offset center of gravity on the rotating eccentric and pressure relief in the inactive cylinder. These solutions eliminated the instability problems.