Dynamic measurements in Reciprocating Refrigerant Compressors

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Today's refrigerant compressor can be characterized as being compact, highly reliable, and having good performance. It is the result of many thousands of man-hours of effort. Because of the investment involved, it behooves the development engineer to use whatever measurement techniques are available to aid him in optimizing the compressor design. For example, endurance testing, both in the laboratory and in the field, has been a standard means of establishing valve reliability. In the past, only approximate methods were available to estimate the valve stresses. As a result, knowledge of potential valve problems could only come from valve failures in test compressors. With the advent of miniature, foil-type, strain gages, it has become possible to measure the dynamic valve strains under operating conditions which are known to be critical to valve life. In fact, work by Ukrainetz and Cohen has shown how this approach can be used to perform accelerated life tests. If the results of work of this type show a valve design to be overstressed, it can be redesigned for a satisfactory stress level before long term testing commences.

Performance tests are an important part of the total testing program for prototype compressors. However, in addition to the standard types of tests, it is now possible to perform valve motion studies and instantaneous pressure measurements in order to better define the valve motion and pressure histories within the compressor. Such measurements provide additional information on valve losses and indicate if changes in manifolding or valve lift can provide a better performing compressor.

It is the purpose of this paper to outline and give examples of various measurement techniques which have been used in reciprocating refrigerant compressors. It is not intended that this paper be an exhaustive survey of all the types of measuring techniques which have been used in compressors. Instead, specific transducers are described which have been used successfully to gain further knowledge about the events which occur within a compressor. Specifically, the techniques will include experimental stress analysis using strain gages, dynamic valve motion measurements, instantaneous pressure measurements, and high speed photography.

EXPERIMENTAL STRESS ANALYSIS

One important means of measuring strains in compressor valves has been through the use of strain gages. The advent of the epoxy-backed foil gage has made this a practical technique in the modern technology of reciprocating compressors. These foil gages, which in themselves are only a few thousandths of an inch thick, can be adhered to valves or other compressor components with epoxy cements adequate to withstand any temperatures normally experienced within a compressor. By using gages whose grid lengths are of the order of 0.015, 0.030 or 0.050 inch in length, it is possible to measure strains in components which are experiencing rather large stress gradients.

Figure 1 is a photograph of a typical strain gage installation on a flexing-ring type suction valve. The approach used here was to minimize the mass of the leads and gage installation. Experience has shown that this approach not only minimizes the mass loading effects on the valve, but prolongs lead and solder tab life. Other than the normal rules regarding cleanliness and careful installation, the art of strain gaging within compressors is primarily in the area of the leads. The normal approach is to bring the leads to a point on the valve which has a minimum displacement during the action of the valve. Figure 2 shows the installation of this valve in a test compressor. As shown, the strain
gage is located on the piston side of the valve. This approach has permitted lead lives of the order of one hour. By running the leads from the gage into a bridge circuit specially suited for this type of dynamic strain work, it is possible to get strain histories of the valve under all operating conditions. Most importantly, it has been possible to measure valve strains in compressors which are installed in normal air conditioning units. Such studies have indicated how the valve strain will vary with variations in unit operation. Typical examples would include periods of flooded operation.

Figure 3 is an example of the strain measured in the aforementioned suction valve. The compressor was a high-speed steel shell compressor operating at a normal air conditioning load. The strain history shows that the valve oscillates over a wide range of displacements during the normal period for passing refrigerant vapor. Also, the strain is composed of both moderate and high frequency components. An analysis of data such as these show that the valve is subjected to high frequency strains resulting from the over-shoot of the unsupported valve sections as well as the lower frequency strains from the fundamental bending mode.

Figure 4 is an example of strain measurements which were made on a spring-loaded ring valve. The valve was installed in a production compressor operating within its normal operating range. The gage was oriented to be tangent to the median diameter of the valve. Because no strain was measured except at the instances of impact, it can be seen that the valve was moving as a rigid body. However, a high frequency valve strain does exist at the instant when the valve strikes the valve stop or valve seat. If a radial gage location is used, the strain history will show the effects of the valve deflecting between the concentric seats during those periods when the valve is closed and a pressure differential exists across it. Measurements made in this manner have been found to agree very well with analytical predictions.

The type of strain measurements being reported here are, of course, dynamic measurements. As such, the effects of instantaneous temperature variations are considered of second order importance. As a check on this assumption, a strain gage was attached to an essentially unstrained component within the cylinder volume and the strain recorded over one complete cycle of compression. Only a very small variation in strain was noted.

**Dynamic Valve Displacement Measurements**

If one makes strain measurements on flexing valves within a compressor, then some knowledge is already available as to how the valve moves. A simple, first mode analysis would say that the displacement of the valve will be proportional to the double integral of the stress. However, proximity type transducers are now available on the market which allow a direct measure of the valve motions in reciprocating compressors. These transducers are, in effect, small inductive coils which send out an electromagnetic field of high frequency. The presence of ferro or paramagnetic materials in the field of the coil causes a change in the impedance of the electromagnetic circuit. This change in impedance, as measured by a voltage, can be related to the distance between the material and the transducer. Generally speaking, transducers are available with effective ranges up to .18 inch. This distance is quite adequate for any valve lift normally used in reciprocating compressors.

This type of transducer is quite non-linear over its full range of sensitivity. However, with the proper pre-calibration of the transducer, it is possible to use these transducers. A wide shift in temperature will cause a shift in the sensitivity of the transducer. However, within reason, these shifts are linear with temperature and it is possible to correct for them.

Figure 5 shows the installation of a proximity probe in the suction valve plate of a high speed hermetic compressor. The schematic sketch accompanying the figure shows a sectional view of the installation. The "potting" of the coil in a steel plate greatly affects the output of the transducer. Therefore, the pre-calibration must be done with the transducer in place.

Figure 6 is an example of the output from such a transducer. Although not measured at the same time as Figure 3, it still confirms the low frequency characteristics of the motion. The rounding off of the peaks is due to the non-linearity of the probe. The high frequency components of the motion are not detected because of the lower sensitivity of the probe.

This same type of probe can be used for spring-loaded ring valves. Tests on such valve assemblies show that when designed properly and operating under normal loads, the valve opens and closes in essentially a "text-book" manner. That is, the valve opens, stays open for gas passage and closes. These probes are of particular value when non-standard valve behavior is suspected. Figure 7 is an example of this
type of behavior. In this photograph, both suction and discharge valve motions are shown. The upper trace with the shorter time span is the discharge valve. Both traces show a condition where the valve does not remain open but rather flutters and/or oscillates during its open period. The particular operating condition under which these motions occurred was one in which an insufficient mass flow passed through the valves to maintain proper valve dynamics. The suction valve motion is also indicative of the pattern which is measured when the lift of the valve is too great for the displacement of the cylinder at a given operating point.

Instantaneous Pressure Measurements

One of the applications in which instantaneous pressure measurements are of interest is in the determination of indicator diagrams. Such diagrams are particularly useful for diagnosing possible problems in the compression process. Of the various measurement techniques being discussed in this paper, pressure measurement is probably the oldest. The literature, for example, details how single point type measurements can be made using balanced-diaphragm\(^3\) or capacitor-type transducers.\(^4\) Strain-gage-type transducers have also been used to measure the instantaneous pressure in the cylinder. This type of transducer can be made to provide an absolute pressure measurement. Recent developments with piezoelectric transducers make these devices stable enough for use in reciprocating compressors. These transducers are of the relative rather than an absolute type. Some method must be found to establish a known pressure from which to determine the other pressures. Mechanical devices are available by which the measured pressure can be constantly referred to an absolute pressure. However, such devices do require more room than is sometimes available. There are also approximate methods by which these pressures can be established. These methods require that some other independent measurement be made, such as valve motion, by which it can be established when, in time, the suction valve closes. The pressure of the gas in the cylinder at this point in time will be very close to the pressure in the suction manifold, which can be measured independently with a test gauge. Pressure fluctuations in the suction manifold are generally found to be quite low. Thus, with one pressure determined and the sensitivity of the transducer known, it is possible to determine the pressure at all other intervals of time during the compression cycle.

Figure 8 is an example of the type of pressure measurement which can be made. This pressure trace was made on a compressor operating at a nominal air conditioning load. The transducer was connected to the cylinder through a probe tube drilled in the housing.

A timing pulse is also evident in the photograph. The pulse is triggered at the top dead center point of the test cylinder. One obvious feature of the trace is that the discharge valve is closing too late after TDC for this particular compressor. It is also evident that high frequency pressure oscillations can exist within the cylinder.

Timing is critical to the determination of the sequence of events. Commercially available magnetic pick-ups which sense a properly placed protuberance on the crankshaft counterweight do a fine job of providing a strong signal.

The probe tube design can be critical in some compressor test work. Ideally, the tube should have a large diameter so as to provide a low impedance. On the other hand, a large diameter will increase the clearance volume of the compressor causing a loss in performance and negating the usefulness of the test data. It is possible to estimate the probe diameter on the basis of acoustic theory for an arbitrary upper frequency limit.\(^5\) The probe can be checked by observing the re-expansion and compression sections of the pressure trace. When the actual initial pressure and temperatures are assumed, these curves have been found to be close to isentropic. The traces should confirm this process path. By measuring the capacity of the compressor before and after installing a probe tube, it is possible to confirm the extent to which the probe affects the performance of the compressor.

Figure 9 is an indicator diagram made from the pressure trace as shown in Figure 8. The diagram confirms that problems exist at or near top dead center. The discharge valve did not close rapidly enough and permitted refrigerant to blow back into the cylinder as the piston started to retreat. In this case, a redesign was made which corrected this situation and the performance of the compressor was improved.

Indicator diagrams, such as shown here, can be used for a diagnostic work in compressors. The area under the enclosed curve is a measure of the indicated work done within the cylinder. Some of that work can be associated with valve losses.
If, in the opinion of the investigator, these losses are too high, then it is possible to make design changes and re-evaluate the indicator diagram to measure the effect of these changes.

**HIGH-SPEED PHOTOGRAPHY**

High-speed photography can be used to make qualitative studies of phenomena which occur within a compressor. Some years ago, we made some simulation studies of the valve motion in reciprocating compressors. It was desirable to try to photograph, using a high-speed camera, valves as they were operating within a compressor. It was realized that this would not be possible as valves are normally installed. However a special compressor was built for this study.

Figure 10 shows a schematic sketch of how this simulation was made. A small compressor was made parasitic to a large compressor. The valves to be studied were within the parasitic compressor. The purpose of the large compressor was to supply an abundance of refrigerant at the desirable pressure and density conditions. The parasitic compressor was an open compressor which could be driven thru a dynamometer. The valve in the inlet side to the parasitic compressor controlled the quantity of refrigerant allowed to pass thru that compressor. The quantity of refrigerant was monitored using an orifice. The valve to be studied was put in series with the discharge valve of the parasitic compressor. This compressor also had a normal suction valve. By controlling the speed of the parasitic compressor and the operating conditions of the large compressor, it was possible to get an order of magnitude simulation for the absolute time of valve motion in the parasitic compressor, the density of the refrigerant, and the mass flow of gas thru the valve.

Figure 11 shows an example of the results of this study. The particular valve being shown here is a four-eared, flexing ring valve. The two photographs are taken from individual frames of a high-speed film. The upper photograph shows the valve in the closed position. In the lower photograph, the valve has just opened. In the film, the perturbations caused in the valve by the impact of the valve against its stop are quite evident. This same approach was used to study a number of different types of suction valves.

**CONCLUDING REMARKS**

An attempt has been made in this paper to outline various experimental techniques which can be used to learn more about specific events in reciprocating compressors. It has been shown it is possible to make valve strain measurements, valve motion measurements, and instantaneous pressure measurements to learn better where potential problems might exist. This approach is fairly new to the industry but already its value has been quite great. Through techniques such as these specific field problems and development problems have been ferreted out quickly and solved. The actual techniques which are used do vary depending on the compressor. It takes the imagination of the investigator to find how he can best obtain his information with a minimum of disturbance to the compressor system. There is also the problem of evaluation or interpretation of the data. However, by being able to make different types of measurements of the same component it is usually possible to find the proper interpretation.

**REFERENCES CITED**


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FIGURE 1 STRAIN GAGE INSTALLATION ON A SUCTION VALVE

FIGURE 2 GAGED VALVE INSTALLATION

FIGURE 3 SUCTION VALVE STRAIN HISTORY FOR A FLEXING RING VALVE

FIGURE 4 SUCTION VALVE STRAIN HISTORY FOR A SPRING-LOADED RING VALVE

FIGURE 5 INSTALLATION OF A PROXIMITY PROBE IN A SUCTION VALVE PLATE
FIGURE 6 VALVE DISPLACEMENT FOR A FLEXING RING TYPE SUCTION VALVE

FIGURE 7 VALVE DISPLACEMENTS FOR SPRING-LOADED SUCTION AND DISCHARGE VALVES

FIGURE 8 INSTANTANEOUS CYLINDER PRESSURE FOR ONE CYCLE OF OPERATION

FIGURE 9 SCHEMATIC FLOW DIAGRAM FOR COMPRESSOR USED IN HIGH SPEED PHOTOGRAPHIC STUDIES

FIGURE 10 INDICATOR DIAGRAM FOR A COMPRESSOR OPERATING AT AN AIR CONDITIONING LOAD
FIGURE 11  HIGH-SPEED PHOTOGRAPHS OF VALVE MOTION