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Fran Simpson
Copeland Corporation

Gordon Lis
Copeland Corporation

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ABSTRACT

Several different methods of measuring cylinder pressures generated during liquid slugging in Hermetic and Semi-Hermetic compressors have been devised. The methods are discussed and compared, and test results are presented. Some interesting aspects of liquid slugging are also discussed. An empirical relation for predicting maximum cylinder pressure as a function of compressor power, bore size, and stroke length is presented.

INTRODUCTION

The need for understanding and measuring the phenomena that occurs during compressor liquid ingestion in an air conditioning, heat pump, or refrigeration system is well known. Most components in the compressor must be designed to withstand the forces generated during that process. The loads and forces generated are usually much larger than during normal operation. Reduction or elimination of these forces could result in reduced costs or higher efficiency compressors, or both. The uncertainty of occurrence and the magnitude of the loads involved probably result in compressor components that are over-designed in many applications.

Liquid ingestion in compressors appears to be a unique problem. Literature searches indicate that very little work has been published in that area. Singh (Reference 1) at Ohio State has carried out some basic work which lists a bibliography of a literature search that was conducted. His conclusion was that very little work had been done, and that there were no other similar disciplines that could be used. As a result, each compressor manufacturer has to develop his own information about liquid ingestion problems, which can be used in the design and development process. Copeland Corporation has been carrying out projects of this nature for several years, and what follows is a summary of what we have learned, and the approaches that we have used. The work described in this paper was carried out on the CR line of compressors. A cross section of a typical compressor is shown in Figure 1. It is a two cylinder hermetic, air conditioning and heat pump compressor. The compressor is suspended in the shell such that the motor is on

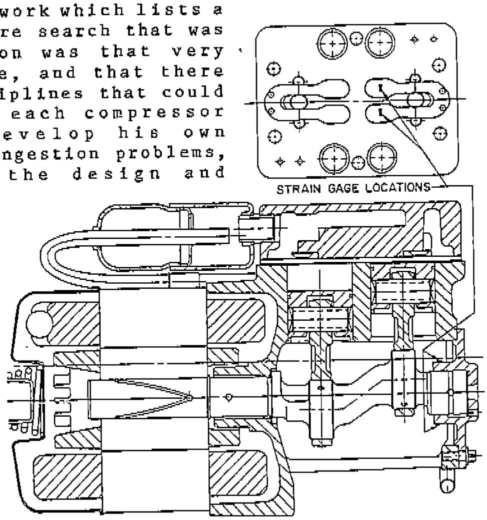

FIGURE 1. COMPRESSORS STRAIN GAGED TO DETERMINE CYLINDER PRESSURES DURING LIQUID SLUGGING.

top with the lower bearing submerged in oil. Each cylinder has two suction ports, with one suction reed per cylinder. Each reed has two "paddles" which are subjected to diaphragm stresses from cylinder pressures.

DATA AQUISITION

One of the most difficult aspects of measuring cylinder pressure, the parameter of primary interest in a liquid ingestion test, is to be able to capture the event with suitable definition. When conducting a liquid ingestion test the compressor is either mounted on a test stand specifically designed to introduce liquid into the compressor, or installed in a system and operated in such a manner as to inject liquid refrigerant into the compressor. Liquid may be introduced to the compressor prior to compressor start (a so-called flooded start test) or while the compressor is running (a defrost test). Some time after the compressor is started (or some time after the liquid injection in a defrost test), rapid, violent pressure rises will be observed in the cylinder. The phenomena is generally called "slugging" in the compressor industry. In attempting to measure this phenomena one has the problem of predicting when it will occur in order to trigger data aquisition devices to gather sufficient data with suitable resolution. Thus one is forced to obtain a data aquisition system with very large storage capabilities to be able to acquire all necessary data, and yet have adequate resolution when the event of interest occurs. We have found that digital oscilloscopes fill all the requirements in this respect, if fitted with four channels of 128,000 word memory. This gives us the capability of scanning all pertinent data, and still having a resolution down to microseconds per point when a typical slug event occurs. This is adequate to accurately describe the events of interest.

INSTRUMENTATION

After having acquired suitable data aquisition systems, initial studies began using piezo-electric type pressure transducers to measure cylinder pressures during liquid ingestion (or "slugging"). Pressures observed using this type of pressure transducer were at times extremely high and often erratic. Figure 2 is a typical example of cylinder pressures measured with two piezo-electric pressure transducers, one on either side of the cylinder. It can be seen that pressures are extremely high, sometimes as high as 4,000 p.s.i., and that they occur very quickly. Pressure rises are very rapid and several "spikes" may be observed where

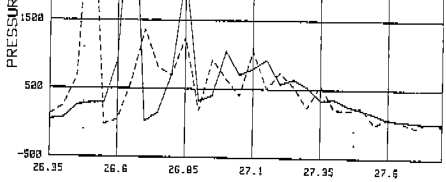

FIGURE 2. CYLINDER PRESSURES MEASURED BY TWO PIEZO-ELECTRIC PRESSURE TRANSDUCERS IN THE BOTTOM CYLINDER.

high pressure will occur during the period of liquid ingestion. Also, as seen in Figure 2, both piezo-electric transducers may not indicate the same pressure, and they are out of phase with one another. The out of phase nature of the data may be explainable since the pressure rises are fast enough to be considered as a wave front which may take some time to travel from one location to another. If one calculates the time required for the wave to travel from one location to the other, this appears to be a logical explanation. However, the measured pressures were of such magnitude that components such as reeds, connecting rods, and gaskets could not have survived. Careful calibration and efforts to prevent "helmholtz" actions from occurring did not result in data that answered those questions. It was finally concluded that liquid droplets were impinging on the transducer face, evaporating, and causing spurious localized readings.

ALTERNATE METHODS

Problems and discrepancies of this nature lead to investigations of other means of measuring pressures in the cylinder which were occurring during slugging. Several methods were devised. Some of these were: (1) strain gages on the valve plate; (2) strain gages on the connecting rod; (3) strain gages on the suction valves; (4) strain gage pressure transducers; and (5) strain gages on strategic locations on the main bearing support members.

Initial attempts were made to strain gage the valve plate in some location where good sensitivity could be accomplished. However, it was quickly learned during attempts to calibrate the strain gages, that we were dealing with a very nonlinear structural system because of the valve plate and head gaskets. Linearity was, of course, desired since it makes the data much easier to analyze and also increases the confidence level in the data that is obtained. It was also found, especially at high cylinder pressures, that the response of the strain gages was not repeatable, and this technique was abandoned.

The next attempt was then focused on placing strain gages on the connecting rod. This was found to be an ideal location from a response standpoint, since it was linear and repeatable, and also was easily calibrated. Any bending or temperature drift was cancelled by using a four gage bridge. T' - .. `', !owever. different calibrations for tension and compression since the connecting rod was short. The digital oscilloscope and its data reduction features enabled us to account for these differences. However, problems were encountered in obtaining the desired amounts of data because of the difficulty in maintaining lead wires from the connecting rod to some suitable station ary point on the compressor body. Figures 3 and 4 are

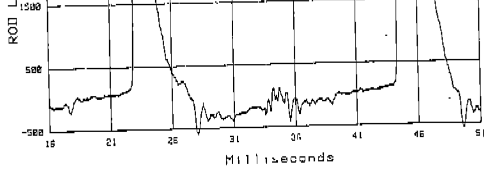

FIGURE 3. CONNECTING ROD LOADS MEASURED BY A STRAIN GAGE BRIDGE.

examples of some of the data obtained from this type of instrumentation. Figure 3 shows two consecutive cyles, all with a connecting rod load of about 4,000 pounds. The measured loads from each cycle are uniform and at much more reasonable levels than those obtained using piezo-electric transducers. It is expected that the structural components will survive a finite number of cycles at these levels. Figure 4 shows an expanded time scale similar to the events shown in Figure 3. Some interesting observations are: (1) the cylinder pressure excursions, even reflected as connecting rod loads, occur very quickly, on the order of one or two milliseconds; and (2) the maximum slug pressure can be developed as early as 100 to 115 degrees before top dead center. There can also be several cycles of extreme pressures per crankshaft revolution (in this case three), and they appear periodic as if some vibrating system were involved.

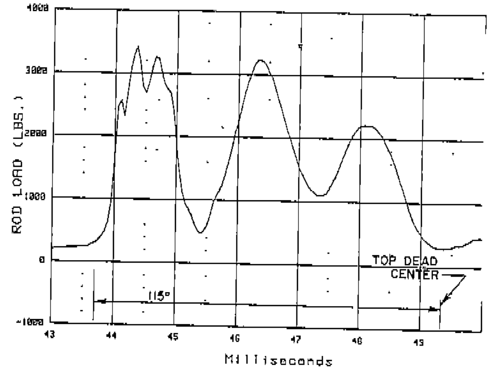

FIGURE 4. EXPANDED TIME SCALE OF CONNECTING ROD LOADS.

Problems with early lead wire failure with instrumented connecting rods always resulted in very little data accumulation for the effort required. The next attempt at better cylinder pressure measurements was to apply strain gages to the suction reeds themselves in locations shown in Figure 1. This again was a difficult problem. However, after a few trials it was found that gages could be placed on the reeds, and after some experience, leads could be designed which eventually lasted for a few hours so that a significant amount of data could be obtained. The strain gages are calibrated by applying hydraulic pressure to the cylinder and obtaining a relation between cylinder pressure and strain gage output.

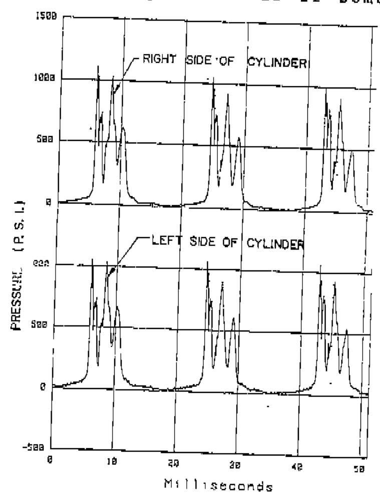

FIGURE 5. CYLINDER PRESSURES MEASURED BY MINIATURE STRAIN GAGE PRESSURE TRANSDUCERS.

During this period of time, we also become aware of the availability of some new types of strain gage pressure transducers. These transducers were much smaller in size than previous strain gage type pressure transducers and could be placed in the body of the compressor.

Tests were then run with the new pressure transducers and strain gages placed on the suction reeds. In order to increase confidence in the accuracy of the results, two transducers were placed in the cylinder and gages on both paddles of the suction reed. The information obtained is shown in Figures 5 and 6. Examination of Figures 5 and 6 reveal, for one of the first times, good agreement between the gages on both suction reed paddles and both pressure transducers. The peak pressures, as measured by all transducers, are very close for all cycles of the slug, around 1,000 p.s.i. The shape of the curves are all very similar and the timing for all events is very nearly the same. This is in contrast to what had been seen in some previous tests where the timing of the peak pressures had occurred at different times, even on the strain gaged reeds. Although no timing mark was included on this test because of limitations on the number of channels of information that could be obtained, one can deduce that again slugging pressures started to build up as much as 130 degrees prior to top dead center.

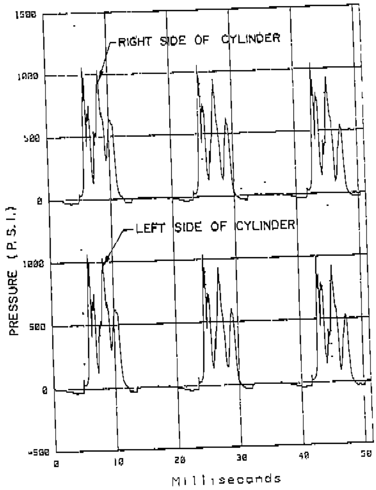

FIGURE 6. CYLINDER PRESSURES MEASURED BY STRAIN GAGES ON TWO PADDLES OF A SUCTION REED.

INSTRUMENTED BEARING

Since all these techniques either required expensive equipment, machining of compressor parts for transducer installation, or lead wires between moving and fixed parts with very short life, other methods were attempted at determining cylinder pressures. An article from N.A.S.A. Tech Briefs (Reference 2) suggested that a bearing sleeve could be used as a load monitoring device. A full bridge strain gage circuit was applied to a lower end main bearing of a CR compressor as shown in Figure 1. The bearing was installed in a compressor and calibrated by applying pressure to the piston with the crankshaft locked at top dead center. The resultant calibration curve is shown in Figure 7. Since high

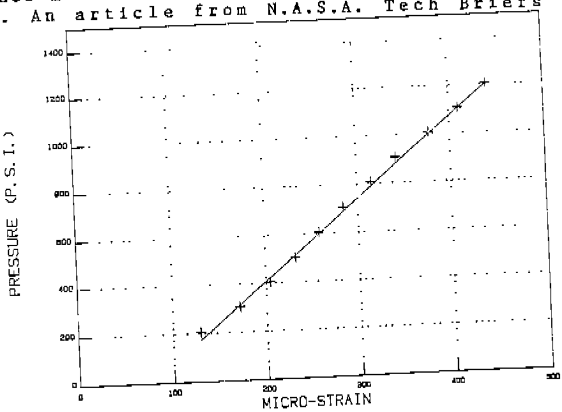

FIGURE 7. CALIBRATION CURVE FOR STRAIN GAGED LOWER BEARING HOUSING.

cylinder pressures have been observed at crank angles from 110 to 30 degrees before top dead center, calibration curves at various angles were investigated. It was concluded that the top dead center calibration curve was very convenient and sufficient for engineering accuracy.

Figure 8 is a trace of cylinder pressures measured with two piezo-electric pressure transducers, and an instrumented bearing, during a mild slug, typical of a slug which occurs during a compressor start. The piezo-electric transducers have been found to be satisfactory for this type of measurement where the pressures are low. The pressure rise is nonviolent, both transducers are in phase with one another and read the same pressure. The instrumented bearing responds in a similar manner. Figure 9 is a trace of cylinder pressure as measured by an instrumented bearing with another more violent slug sequence, showing several cycles. It can be seen that both cylinder number one (bottom cylinder) and cylinder number two are undergoing a series of pressure excursions. This is not always true. Traces have been observed where only the lower cylinder had relatively high pressure loads. Here the pressure rise can be seen to be very rapid and violent. Typical time periods for the rise and fall are on the order of one to two milliseconds. Again, there appears to be a system resonance taking place since several cycles can be observed during one compressor cycle.

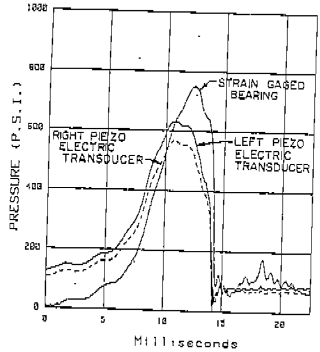

FIGURE 8. CYLINDER PRESSURES MEASURED BY PIEZO-ELECTRIC TRANSDUCERS AND A STRAIN GAGE BEARING DURING A MILD SLUG.

One further test was carried out to verify that the strain gaged bearing transducer was a reliable indicator of cylinder pressures. Two of the new miniature strain gage pressure transducers, strain gages on the two ports of the suction reed, and the strain gaged bearing were installed in a compressor, and simultaneous readings were taken for comparison. The compressor was placed on one of the more severe system tests and data recorded during violent slugs. The data was then plotted as seen in Figure 10. The average of the two maximum pressure readings from the pressure transducers

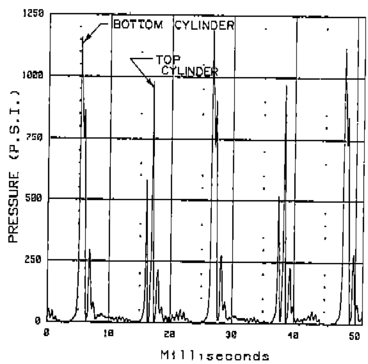

FIGURE 9. CYLINDER PRESSURES MEASURED BY AN INSTRUMENTED BEARING DURING A VIOLENT SLUG.

was plotted as the independent variable on the abscissa. It can be seen that all readings fall within a +/-20% region, and most fall within +/-10%. The strain gaged suction reed does give results that agree more closely over a larger range with the pressure transducers. However, the instrumented bearing gives a very good indication of the general level of the cylinder pressures and is within 20% of the actual pressure. It is a very desireable transducer considering the simplicity and ease of use for continuous operation.

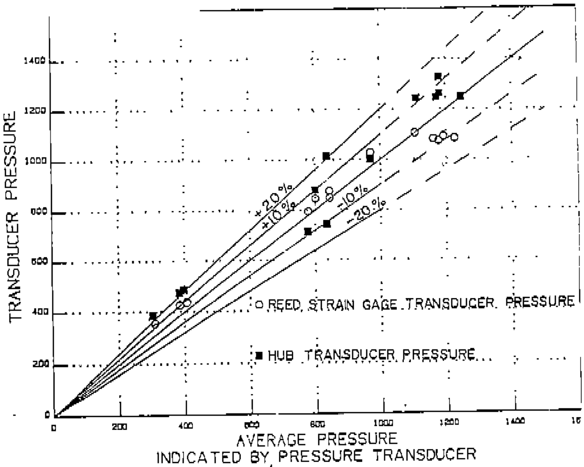

FIGURE 10. CYLINDER PRESSURE CORRELATION BETWEEN STRAIN GAGED BEARING HOUSING, STRAIN GAGED SUCTION REED PADDLES, AND PRESSURE TRANSDUCERS IN BOTTOM CYLINDER.

SYSTEM RESULTS

After developing the strain gaged bearing housing to the point where it was considered acceptable for measuring cylinder pressures, it was decided to use it for determining pressures in a compressor during liquid ingestion on a system. The system was set up with a standard compressor and instrumented with the strain gaged bearing housing. It was found that large quantities of liquid could be induced into the compressor by operating the system at high condensing pressures for a short period of time and then shutting the unit off. During the shut down period, liquid from the condenser was driven through the evaporator by the high pressure differential into the compressor (this happens with a capillary tube system). When the compressor was restarted, extreme cylinder pressures resulted and many cycles could be observed. The strain gaged bearing was an excellent device to study this phenomena because of its reliability and repeatability. Traces of the cylinder pressures observed during this type of testing are shown in Figure 11. It can be seen that the pressures are very high, that each rotational cycle is composed of many pressure cycles in the cylinder, and that both the upper and lower cylinders are slugging. During some projects, literally

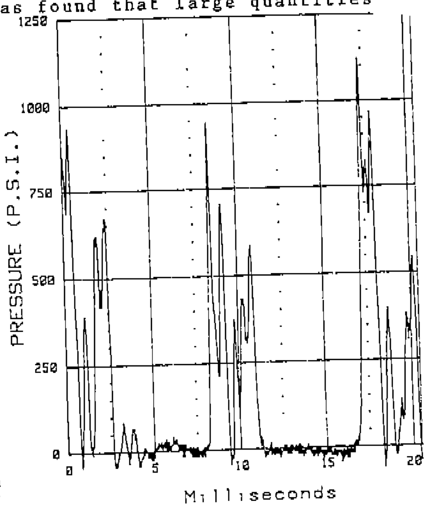

FIGURE 11. CYLINDER PRESSURE OBSERVED IN A SYSTEM FLOODED START AS MEASURED BY A STRAIN GAGED BEARING HOUSING.

hundreds of tests of this nature have been conducted with the strain gaged bearing, and the data recorded. In order to avoid lengthy plotting procedures, the data is usually recorded in tabular form, such as that shown in Table 1. The parameters that are of interest are the number of pressure excursions above an arbitrary level (usually 500 p.s.i.), and the actual values of each pressure. This is sufficient information to give to designers for component design work.

TABLE 1
Cylinder Pressures (P.S.I.)

	100% CHARGE	130% CHARGE	160% CHARGE
	444	895	1196
	717	909	1252
	759	951	1196
	636	857	1389
	650	937	1144
	608	937	1210
	825	801	1277
	829	815	1224
	745	703	1238
	811	895	1210
AVERAGE	**702**	**870**	**1234**

EMPIRICAL RELATIONSHIPS

Over a long period of time many liquid ingestion tests have been carried out, on flooded start and defrost test stands, on air conditioning units in load rooms and psychrometric rooms, and on units in open rooms. When slugging occurs it has been found that the maximum pressure (P) that can be observed for any similar series of compressors can be expressed empirically as a function of the compressor bore (D), stroke (S), and nominal motor horsepower (HP). The equation that fits the Copeland CR line is:

$$P = \frac{K}{SD^2} (HP)^{1.12} \qquad \text{Equation 1}$$

Equation (1) can be rearranged to show that the maximum torque reaction is a function of the compressor motor power:

$$(FORCE)(MOMENT\ ARM) = K_1(PD^2)(S) = K_2(HP)^{1.12} \qquad \text{Equation 2}$$

Figure 12 is a plot of equation (1) for the CR line of Copeland compressors, and the resulting maximum pressures that have been observed for that line of compressors. It can be seen that although there is some deviation, equation 1 fits well enough for engineering design work when sizing components such as reed thickness, connecting rods, crankshafts, valve plates, and other structural parts of the compressor.

CONCLUSION

The conventional piezo-electric pressure transducer is not suitable for measuring cylinder pressures during liquid ingestion in the reciprocating compressor. Methods such as placing strain gages on the connecting rod or on the suction reed are capable of

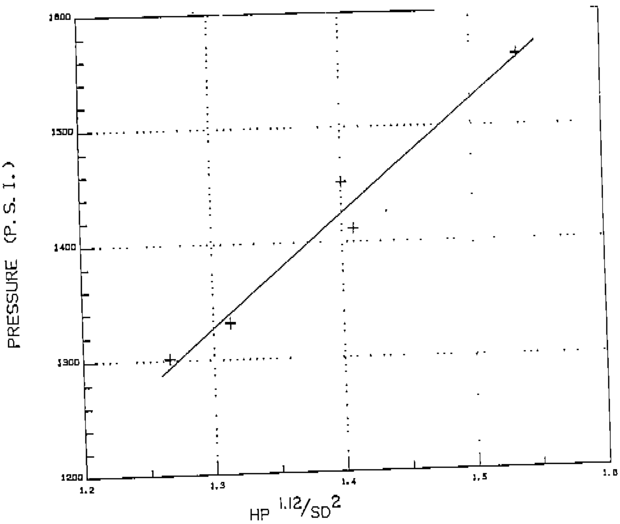

FIGURE 12. CYLINDER PRESSURES AS A FUNCTION OF THE COMPRESSOR SIZE PARAMETER.

measuring cylinder pressures accurately, but usually results in long periods of test time because of strain gage and lead wire reliability. A new type of miniature strain gage pressure transducer has been utilized with very good results. If very long instrumentation life is desired with minimum installation effort, a strain gaged bearing support structure has been shown to be a useful method of measuring cylinder pressures during liquid ingestion in the reciprocating compressor. Finally, an expression can be quantified to empirically determine the maximum reaction that will occur in a similar line of compressors, given the maximum observed reaction level in one compressor. In its simplest form:

$$\text{Maximum Torque Reaction} = K_2(\text{Available Nominal H.P.})^{1.12}$$

ACKNOWLEDGEMENT

Over a long period of time, the skills and expertise of several engineers and technicians have contributed to our understanding of liquid ingestion. Some of those people are Tim Quellhorst, Dave Keener, Jim Meyer, Rick Snider, and Frank Schwieterman.

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