Methods for Detection of Lubrication Failure Applied to a Swashplate Compressor

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Measurement of Oil Circulation and Compressor Lubrication in a Mobile Air Conditioning System
C. Cusano, N. R. Miller, T. A. Newell, and P. S. Hrnjak, Principal Investigators

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ABSTRACT

Understanding lubrication failures at the shoe/swashplate contact of automotive swashplate compressors will greatly enhance the reliability of the air conditioning system. Maintaining proper lubrication is not always possible during transient conditions. Therefore, a method for detection of lubricant loss is of great interest to the automotive industry. Three methods for detecting lubrication loss were examined: contact resistance, acoustic emission, and dynamic pressure oscillations.

A mobile air conditioning test stand capable of recording many system parameters was used. Oil return to the compressor was monitored using an oil separator and a refrigerant/oil concentration sensor. Data were taken during steady oil return rates and after oil shut off.

The electrical contact resistance between the shoe and swashplate was used to indicate changes in the lubrication conditions at this critical interface. Measurements were taken at two oil return rates, during steady oil return tests. Preliminary results show that the minimum contact resistance is independent of the steady oil flow rates tested.

In addition to the contact resistance, an acoustic emission (AE) sensor and a dynamic pressure transducer (DPX) were used to monitor oil film breakdown after oil shut off. Preliminary data indicate that the DPX may be an early indicator of low oil circulation. Even after several hours of operation after oil shut off, the magnitude of the contact resistance indicated no oil film breakdown had occurred. It was determined that the AE sensor is probably not an adequate indicator of lubrication breakdown.

INTRODUCTION

Failure of swashplate compressors in automotive air conditioning systems due to inadequate oil circulation is not well understood. The primary failure mode of swashplate compressors is scuffing at the shoe and swashplate interface.

In order to better understand the scuffing event, there is a need to study the operating conditions during failure. Several methods for possible early detection of failure have been developed. These methods can be used during normal operation, start up and quasi-steady clutch cycling. The primary method for early failure detection is a contact resistance measurement between the shoe and swashplate.

Previous work by Yoon et al. [1999] has shown that a substantial reduction in the resistance across this contact indicates a destruction of the protective surface layer, ultimately resulting in a scuffing failure. In conjunction with the compressor instrumentation, suction line oil circulation rates are controlled and monitored to see the effects of varying oil circulation rates on compressor lubrication. Acoustic emission and sound pressure data are also taken as non-intrusive methods of early failure detection. Data from these measurements are correlated with the results from contact resistance and oil circulation measurements.

Although these results are only preliminary, they are encouraging. Work on these techniques is still ongoing. Future work will include measurements that incorporate all standard components for an automotive air conditioning loop. Tests will include conditions where low oil return is likely. Transient conditions such as slugging during start up and clutch cycling conditions will be examined. Finally, data using these techniques may lead to a practical method for detection of lubrication failures.

EXPERIMENTAL SETUP

TEST LOOP

The test setup used in these experiments was constructed using standard automotive air conditioning components. This system includes a swashplate compressor, a fixed orifice tube expansion device, and a suction line accumulator. For the experiments, the suction line accumulator was replaced with an oil separator, as seen in Figure 1. Airflows over the evaporator and condenser are controlled with blowers and variable speed drives to simulate different driving conditions. Similarly, a variable speed motor controls the speed of the compressor. This loop is instrumented with appropriate temperature and pressure sensors at all critical points throughout the loop to measure air conditioning performance as described in Weston et al. [1996].

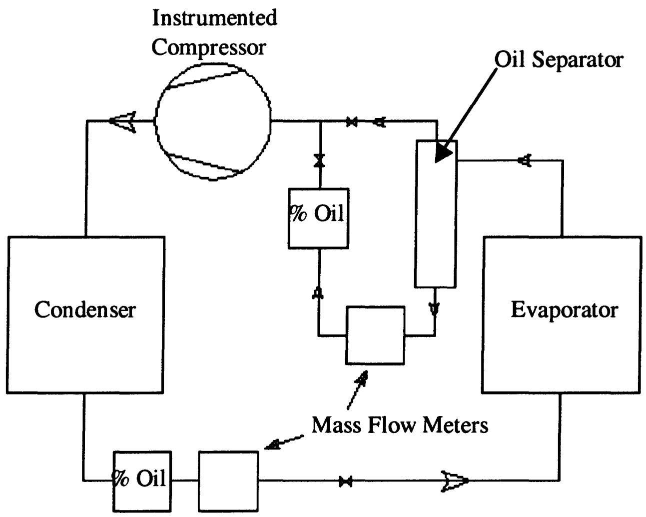

Figure 1. Simplified Loop Schematic

The oil separator on the suction side of the compressor is used to meter oil return to the compressor. To obtain an accurate measurement of oil return using a mass flow meter, the concentration of refrigerant in the oil must be measured. This measurement was made using a sensor that relates changes in the refractive index of the mixture to the concentration of refrigerant in the mixture, a technique described in Newell [1996] and Wandell et al. [1998]. The percent of oil in circulation is measured in the liquid line with a sensor of the same type. This sensor, in conjunction with a mass flow meter in the liquid line, allows for two independent measurements of steady oil circulation to be taken.

COMPRESSOR INSTRUMENTATION

Contact Resistance Instrumentation

In order to measure the electrical contact resistance across the shoe and swashplate interface, a circuit was designed to isolate this resistance. Since the piston was in constant motion, a sliding contact was mounted on the side of the piston as seen in Figure 2. A series of grooves were machined which allowed brushes to ride in them and maintain the necessary electrical contact. Plating the contact area with gold further enhanced the effectiveness of this contact. The pistons are ringed with an electrically insulating material so that a short circuit could not occur between the piston and compressor housing. Also, care was taken to isolate the bridge of the piston from the edge of the swashplate by the addition of inlaid non-conducting polymer pads on the piston bridge. From the shoe/swashplate interface, the circuit continues through the shaft to a slip ring on the end of the shaft. This slip ring is the contact point of the circuit outside the compressor.

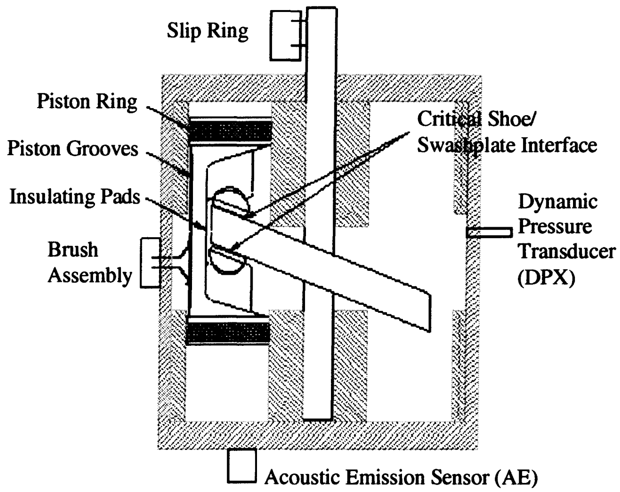

Figure 2. Schematic of Instrumented Compressor

In order to protect the data acquisition device, two 25Ω resistors are connected in series with the contact resistance so that a short circuit would not occur at low values of this resistance. A voltage divider circuit, as seen in Figure 3, was used to determine the contact resistance from the measured voltage across the shoe/swashplate interface. The voltage drop applied across the circuit was one volt. The data acquisition hardware allowed data to be taken at up to a 50 kilosamples per second. Contact resistance data were taken at rate of 5 kilosamples per second.

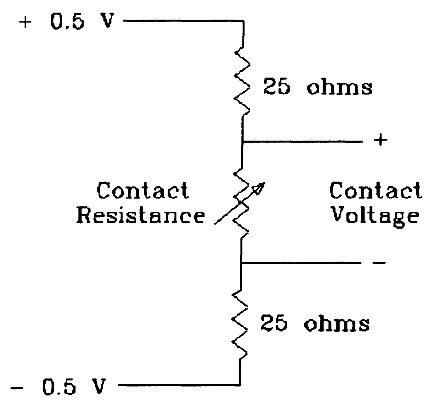

Figure 3. Contact Resistance Circuit Schematic

AE and DPX Instrumentation

The acoustic emissions sensor was used as a non-intrusive method for detecting oil film breakdown. The sensor was mounted on the outer housing of the compressor as shown in Figure 2. The bandwidth of this sensor is 1 MHz, which allows for detection of high frequency acoustic emissions. Data for the acoustic sensor were acquired with a digitizing oscilloscope with a maximum bandwidth of 100 MHz.

Another, slightly more intrusive, method used for detecting oil film breakdown is a dynamic pressure transducer. The transducer was mounted in the sliding contact cavity close to the swashplate, as shown Figure 2. The bandwidth of this transducer is 125 kHz. The dynamic pressure transducer data were acquired at 50 kilosamples per second with the same hardware as the contact resistance measurement.

RESULTS AND DISCUSSION

Two tests were run using the described instrumentation to observe changes under varying compressor conditions. During the first test, only the contact resistance method was used to determine the effect of varying oil circulation. For the contact resistance test, steady oil return flow rates showed cyclic contact resistance under steady conditions.

During the second test, data were taken after the oil to the compressor was shut off. All three instrumentation techniques were used. Noticeable changes were observed immediately after the oil circulation was shut off for the DPX signal. No significant change was observed for the contact resistance measurement.

STEADY STATE TEST DATA – CONTACT RESISTANCE RESULTS

The steady oil return test was run to mimic standard idling conditions. These idling conditions included a compressor speed of 800 rpm and high superheat at the evaporator exit. The loop was run continuously until equilibrium was reached. This was defined as the condition when oil circulation rates into and out of the compressor were approximately the same. Once steady conditions were reached, a sample of data was taken. The contact resistance was compared under two levels of equilibrium oil return. These steady oil return rates were 5.8 g/min and 15.4 g/min, which correspond to 0.5% and 1.3% oil circulation rates, respectively. At these oil rates, no oil film breakdown is expected.

The instrumentation included an optical position sensor mounted on the end of the compressor. This allowed the contact resistance data to be correlated to the position of the instrumented piston throughout the cycle. The raw contact resistance data demonstrated large step changes. These results are expected due to the complex dynamics of the piston compression cycle. Also, minor interactions between asperites could contribute to these abrupt changes in resistance as described by Furey [1961]. The variation of the contact resistance from cycle to cycle was determined to be approximately the same. Therefore, an averaging scheme was used. The averaging technique used a position sensor to examine a full revolution of the shaft. The data were then averaged point by point through the revolution over approximately 100 cycles. The results from this averaging are shown in Figure 4. It should be noted that, for detecting oil film breakdown, this averaging should usually not be used to avoid concealing a film failure within the average. For such detection, the raw data are needed to determine the exact time at which film breakdown occurs.

Note that the pistons experience two compressions per revolution, one compression per piston head. The dotted line in Figure 4 corresponds to a simplified shoe loading calculation. This consists of a polytropic compression of the refrigerant and an inertial loading of the piston. At low values of loading, the resistance remained high, on the order of 10kΩ. As the shoe load increased, the contact resistance was reduced to approximately 10Ω through a series of oscillations. The expected value of resistance when oil film breakdown occurs should probably be less than 1Ω.

Figure 4 shows a comparison of two oil return rates. For the oil circulation rates used, oil film failure does not occur even though some asperity interaction is possible. For both oil return rates the highly loaded portion of the cycle has approximately the same contact resistance. This demonstrated sufficient oil lubrication for both oil return rates.

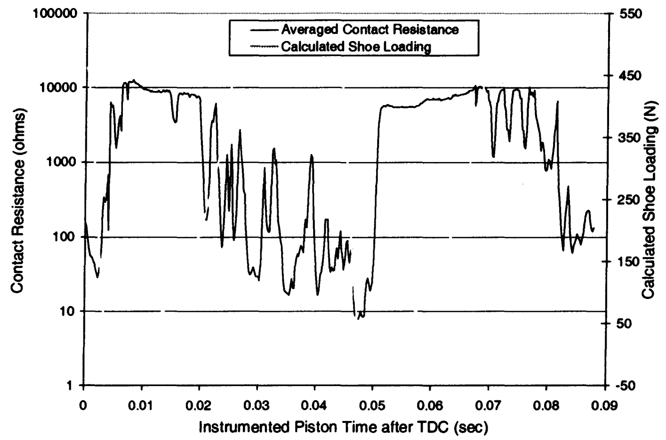

Figure 4a. Averaged Contact Resistance for 1.3% Steady Oil Circulation Rate

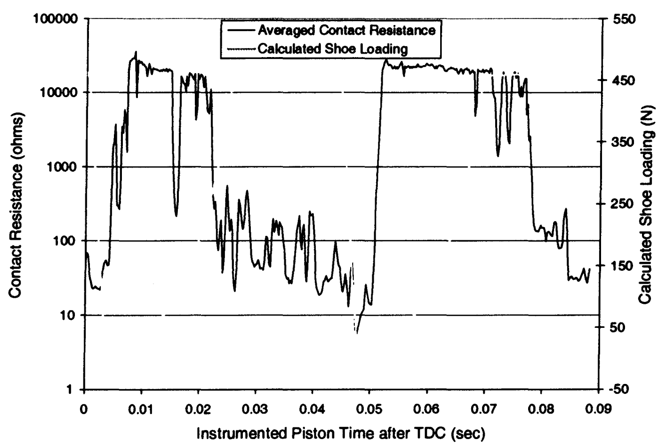

Figure 4b. Averaged Contact Resistance for 0.5% Steady Oil Circulation Rate

OIL SHUT OFF TEST DATA

Using the same compressor, a second test was conducted to determine if the DPX or AE sensor could detect deteriorating lubrication conditions after oil shut off and if the data obtained from the sensors could be correlated to changes in contact resistance. The test stand was run under the same operating conditions as the steady oil return rate tests. Initially, the oil rate was set to 3.9 g/min. This corresponded to a 0.3% oil circulation rate, a condition where the compressor had low lubrication, but with no oil film breakdown. Sensor baseline data were taken at these conditions. Next, the oil return was shut off and residual oil continued to flow to the compressor. Data were taken as this oil flow rate decreased and the residual oil in the compressor decreased as well.

DPX Data

The response of the DPX during well-lubricated conditions appeared regular and repeatable. Initially, no high frequency event was observed, as seen in Figure 5a. Soon after the oil was turned off, several cyclic events appeared. This can be seen in Figure 5b. As more time passed without oil in circulation, the events became more prominent.

There appears to be some events with higher amplitudes. This may be due to sensor location. The DPX is located in the upper half of the housing. The position of the sensor relative to the signal could make the sensor more sensitive to events occurring closer.

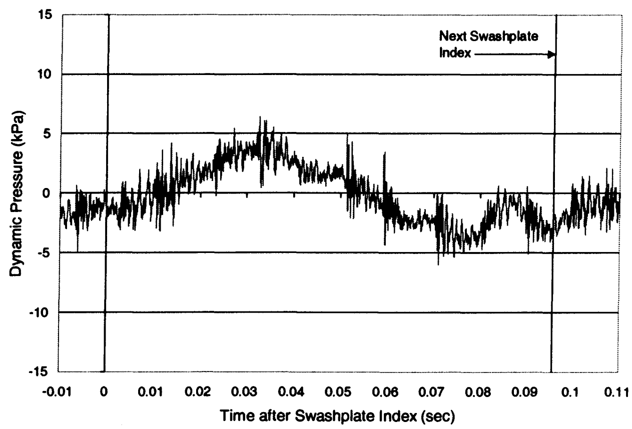

Figure 5a. Dynamic Pressure (DPX) Data for 0.3% Steady Oil Circulation Rate

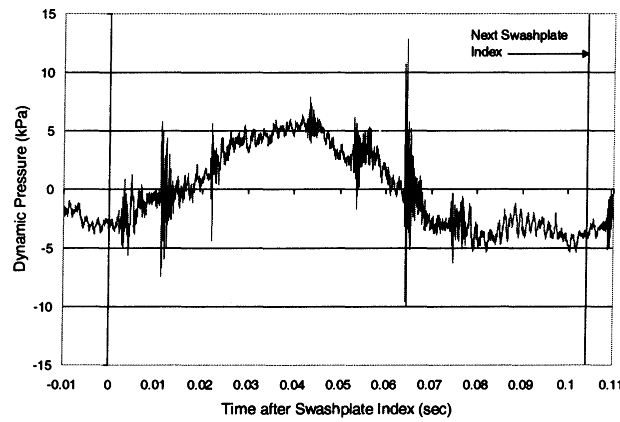

Figure 5b. Dynamic Pressure (DPX) Data 18 Minutes after Oil Return Was Shut Off

Contact Resistance Data

The contact resistance data during the oil shut off test showed the same trend as seen in the steady oil circulation rate tests. Both immediately and 18 minutes after the oil was shut off, resistance plots showed adequate lubrication as seen in Figure 6.

The average value of contact resistance is higher than the steady state test value. This may be due to a running-in process during which the roughness of the tin coating on the swashplate was reduced.

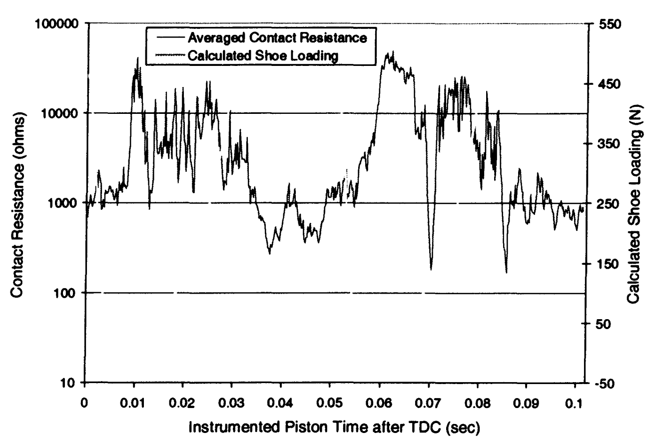

Figure 6a. Averaged Contact Resistance for 0.3% Steady Oil Circulation Rate

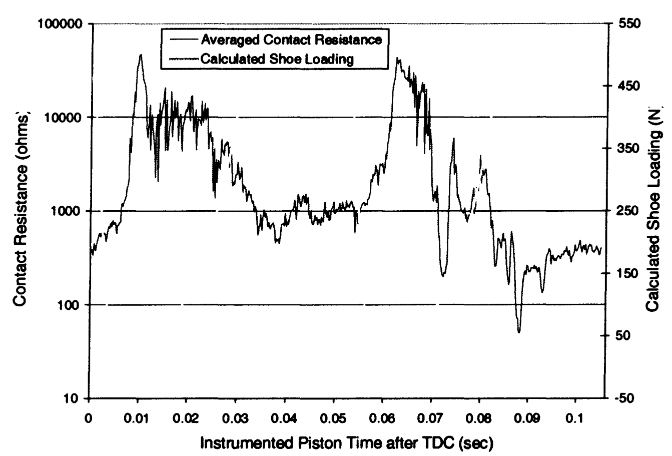

Figure 6b. Averaged Contact Resistance 16 Minutes after Oil Return Was Shut Off

AE Data

AE sensor data did not demonstrate a significant change during the oil shut off test. It is believed that, mainly because of the mounting limitations, there was a poor coupling between the shoe/swashplate interface and the sensor. A signal was detected during both good and poor lubrication conditions, but its source could not be identified. Therefore, it was determined that the AE sensor was not a good indicator of oil film breakdown.

As previously stated, no oil breakdown was observed for several hours of operation after the oil was shut off. A tear down of the compressor showed no visible wear on the swashplate nor on the shoes. This agrees with the contact resistance data taken which shows that the lowest resistance achieved was about 10Ω. Tests will be conducted in the future which will subject the compressor to operating conditions which are expected to cause lubricant breakdown. Among these conditions include slugging and startups when the refrigerant can act as a solvent; removing residual oil from the surfaces of the compressor.

CONCLUSION

A real-time resistance sensor was used to measure contact resistance between the shoe and swashplate of an air conditioning compressor during 15.4 g/min and 5.8 g/min oil circulation under steady state conditions. In addition, the resistance sensor was complemented with both AE and DPX sensors to determine if these sensors could be used to detect oil film breakdown after the oil was shut off to the compressor.

Results of the contact resistance experiment showed that for the flow rates examined, sufficient lubrication was present for the steady state tests. This was demonstrated in the highly loaded portion of the cycle where the resistance was on the order of 10Ω. During oil film breakdown, a contact resistance less than 1Ω is expected.

For the oil shut off test, after running several hours without oil return, the contact resistance indicated that no oil film breakdown had occurred.

The DPX signal revealed several cyclic events as oil return ceased. These events occurred soon after oil was shut off. On the other hand, the contact resistance changed slowly after several hours of running after oil shut down. The shoe/swashplate sliding interface is a possible cause for the observed behavior of the DPX. However, other sources could cause these signals including the valves operating with different levels of oil coating or bearing vibration. As the amount of residual oil in the compressor decreased, the DPX signal intensified. The AE signal was inconclusive. Physical limitations prevented a good signal path from the surface of interest.

Based on the preliminary data obtained, it is believed that on-line monitoring of contact resistance and/or dynamic pressure may be effective means of detecting lubrication breakdown in automotive air conditioning compressors.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AE: Acoustic Emission

DPX: Dynamic Pressure Transducer

TDC: Top Dead Center