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Christopher R. Laughman
MIT

Roderick R. Lal Foy
MIT

Warit Wichakool
MIT

Peter R. Armstrong
MIT

Steven B. Leeb
MIT

See next page for additional authors

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Authors
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Christopher R. Laughman[1*] Roderick LaFoy[1] Warit Wichakool[1] Peter R. Armstrong[1]
Steven B. Leeb[1] Leslie K. Norford[1] John Rodriguez[2] Kai Goebel[3]
Ann Patterson−Hine[3] E. C. Lupton[2]

[1]Massachusetts Institute of Technology
Cambridge, MA 02139
{crlaugh, rlafoy, waritw}@ mit.edu
{parmstr, sbleeb, lnorford}@ mit.edu

[2]NEMOmetrics Co.
Brighton, MA 02135
NEMOmetrics@ aol.com

[3]NASA Ames Research Center
Moffett Field, CA 94035
{kai.goebel,ann.patterson-hine}@ nasa.gov

ABSTRACT

The ingestion of liquid refrigerant into the compressor, also known as liquid slugging, has been established as a common cause of failure in reciprocating compressors. Due to the difficulty of directly identifying the presence of liquid in the compressor cylinder, this paper proposes and develops a method of identifying slugging-induced overpressures in reciprocating compressors by analyzing the electrical power flowing into the compressor motor. In order to validate the performance of this detection method, measurements are also made of the cylinder pressures, the discharge pressure, and the compressor speed. Results from the experimental implementation of these fault detection techniques are provided to illustrate the accuracy by which electrical measurements can be used to identify this mechanical fault.

1 INTRODUCTION

The ingestion of liquid refrigerant into the compressor, also known as liquid slugging, is a common and potentially damaging fault condition affecting air-conditioning and refrigeration compressors. This phenomenon occurs when liquid refrigerant enters the compressor through the suction port, either during startup or during steady-state operation. A variety of conditions can give rise to liquid slugging; for example, cool environmental conditions can cause the refrigerant vapor in the suction line to condense when the compressor is not in operation, so that the condensed liquid flows into the compressor when the compressor turns on. This type of liquid slugging is also referred to as a flooded start. Malfunctioning expansion valves or an excessive refrigerant charge can also cause the amount of liquid entering the evaporator to exceed its capacity while the compressor is in operation, causing liquid slugging. In order to distinguish this fault condition from flooded starts, liquid ingestion during continuous compressor operation will be referred to as *steady-state* liquid ingestion.

Previous fault surveys of packaged unitary air-conditioning equipment (Breuker and Braun, 1998, Cunniffe *et al.*, 1986) suggest that liquid slugging is quite common, and is one of the principal causes of faults in compressors. While a variety of different faults can be directly caused by liquid slugging, such as bent reed valves or damaged pistons, connecting rods, and crankshafts, slugging is also indirectly responsible for other faults, such as the increased carryover of oil into the system as refrigerant, which has been absorbed into the compressor oil, starts boiling upon startup (Cunniffe *et al.*, 1986). Research has shown that reciprocating compressors are particularly susceptible to liquid slugging, as compared to other types of compressors, due to the relatively steep volume compression gradient (Liu and Soedel, 1994).

A number of different approaches to the detection and experimental characterization of liquid slugging have been explored in previous research. Singh *et al.* (1986) experimentally investigated liquid slugging by measuring the cylinder pressure directly, and developed two distinct models of the physical system which were able to reproduce the observed behavior fairly well. Simpson and Lis (1988) also studied the experimental aspects of the liquid slugging problem by testing a number of different methods for measuring the cylinder pressure. They found that many of the measurement techniques, such as mounting strain gauges on the valves, produced spurious results that were either inconsistent with the physical observations of the system or were non-repeatable. After a variety of experiments, the authors found that the most repeatable and accurate measurements were obtained by using strain gauges to measure the force on the bottom of the crankshaft bearings.

One alternative technique for identifying the presence of liquid in the compressor cylinder is developed in Laughman *et al.* (2006). Rather than directly measuring cylinder pressure, this identification method uses the observation that the temporary increase in the cylinder pressure due to the presence of liquid causes a momentary increase in the load on the compressor motor. The presence of liquid can thus be inferred from deviations in the currents measured at the motor terminals. Experiments carried out in this paper indicate the viability of this technique for identifying liquid slugging.

While the methods outlined by Laughman *et al.* (2006) suggest a new direction for developing liquid slugging detection strategies, experimental limitations prohibited the authors from directly measuring the cylinder pressure to verify the presence of liquid in the cylinder, thereby cross-validating the observations made from the electrical measurements. The present research was therefore conducted to obtain this experimental validation by directly measuring the cylinder pressure and the motor speed, and correlating the deviations in these variables during a liquid slugging event with the corresponding changes in the motor currents. By validating the performance of this electrical method of liquid slugging detection, it will be possible to study the incidence and severity of liquid slugging phenomena in the field without installing sensitive and costly instrumentation.

This paper proceeds by first reviewing the analytical techniques used to process the electrical measurements needed to identify a liquid slugging event, and then proposing a set of mechanical measurements by which this fault detection method can be cross-validated. Once the overall framework of the method has been established, the experimental apparatus will be described, and the effects of injecting different amounts of liquid on the electrical and mechanical measurements will then be illustrated. This analysis will focus exclusively on identifying steady-state slugging.

2 SIGNAL PROCESSING OF MOTOR CURRENTS

During a steady-state liquid slugging event, the compressor motor must supply more torque to the piston to move the relatively incompressible liquid through the discharge port than would be required if there was only vapor present in the cylinder. Such an observation can be used to design a processing method which can identify momentary changes in the mechanical load of the motor and thereby detect the occurrence of liquid slugging by looking for such deviations. While one simple detection method could consist of simply analyzing the raw currents flowing into the compressor motor, this would be problematic for two reasons. The first disadvantage of directly analyzing the stator currents is that the changes in the currents due to torque variations are effectively modulated on top of the 60 Hz frequency of the electric utility, so that a detection method must demodulate the waveform to identify the presence of slugging. In addition, the current flowing into each stator winding during the motor startup transient is dependent on the electrical angle at which the motor was activated. This would make it difficult for a detection method which analyzed the current waveforms during that initial startup period to distinguish between the effects of a varying initial electrical angle and the effects of liquid slugging.

One processing method which minimizes these effects involves the transformation of the 3-phase set of motor currents from the laboratory frame of reference into a reference frame which rotates synchronously with the balanced 3-phase set of sinusoidal voltages driving the stator windings of the induction motor. This method of processing the motor currents is also known as Park's transformation (Krause *et al.*, 1986). Specifically, it can be written as the following:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{0s} \end{bmatrix} = \left(\frac{2}{3}\right) \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin(\omega t) & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{1}$$

In this particular application, the angle ωt is synchronized with the angle of phase A of the utility, as referred to the neutral point. While compressor motors are typically wound in a delta configuration, the measured phase-to-phase voltages can be shifted and scaled to synthesize an equivalent set of neutral-referenced voltages. The effect that this transformation has on the set of motor currents can be seen in the motor startup simulation shown in Figures 1 and 2; the raw currents are illustrated in Figure 1, while the transformed currents i_{ds} and i_{qs} are shown in Figure 2. By looking

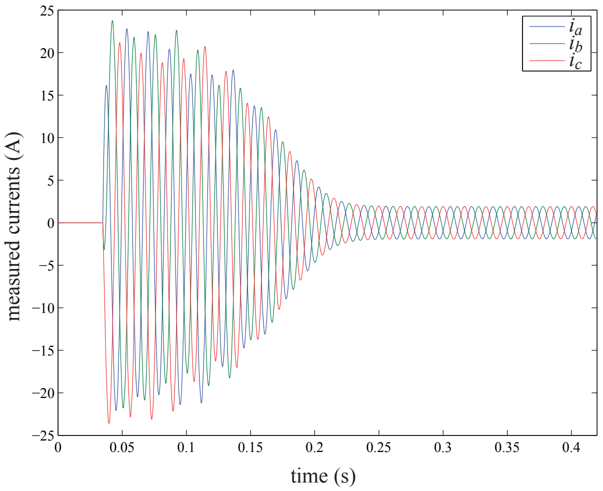

Figure 1: Plot of i_a, i_b, and i_c measured flowing into the motor during startup.

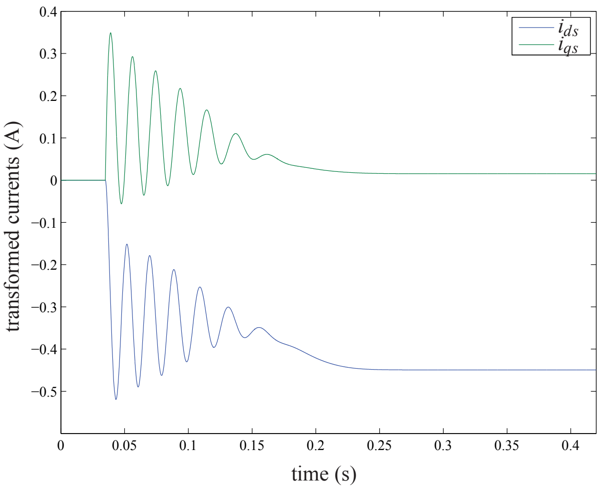

Figure 2: Plot of i_{ds} and i_{qs} after transforming measured currents into the rotating reference frame.

at the steady-state portion of the simulation, one can see that the waveform has no time-varying components, making it easier to identify sudden changes due to faults such as liquid slugging.

While one main benefit of this processing method is the elimination of the usual time-varying components of the signal, another benefit can be seen by writing down an expression for the electrical torque T_e produced by the motor in terms of these rotating reference frame variables, as given in (2),

$$T_e = \left(\frac{3}{2}\right) P \left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right), \tag{2}$$

where P is the number of pole pairs of the machine, and λ_{ds} and λ_{qs} are terms denoting the d- and q-axis magnetic flux for the stator, respectively. This equation makes it clear that the torque produced is dependent upon two components proportional to the currents i_{ds} and i_{qs}. The analysis of both of these currents will therefore prove to be useful in identifying liquid slugging. While the torque is nominally dependent upon both of these variables, changes due to liquid slugging often will appear predominantly in one of them.

When implementing this fault detection method in an experimental setting, it is uncommon to find that the utility voltages are perfectly balanced and sinusoidal, as is the case in the previous simulation. To identify the variations due to changes in the torque, it is thus necessary to filter these transformed variables to suppress the processing artifacts caused by the non-sinusoidal characteristics of the utility. Due to the periodic, structured nature of this noise, a multi-resolution wavelet filter bank with fifth-order Daubechies wavelet filters (as implemented in the Matlab wavelet toolbox) was used to eliminate the high-frequency detail coefficients of this signal and leave only the approximation coefficients behind (Mallat, 1999). The deviations in the filtered signals i_{ds} and i_{qs} caused by liquid slugging are visually discernible in these approximation coefficients, and also detectable by a simple thresholding or differencing algorithm. This will be clear when looking at the data in section 4.

3 EXPERIMENTAL APPARATUS

The experimental platform used in this research was a split air-conditioning unit manufactured by International Comfort Products, with a nominal cooling capacity of 3 tons and a refrigerant capacity of 96 oz of R-22. A 3/4 hp Copeland semi-hermetic two-cylinder compressor was installed in this system to facilitate the construction of the experimental instrumentation. Though this compressor is somewhat undersized with respect to the condenser and evaporator, both the ease with which this compressor can be adapted to experimental requirements and the fact that this research is primarily concerned with measuring deviations from steady-state behavior justify its use. The following dimensions

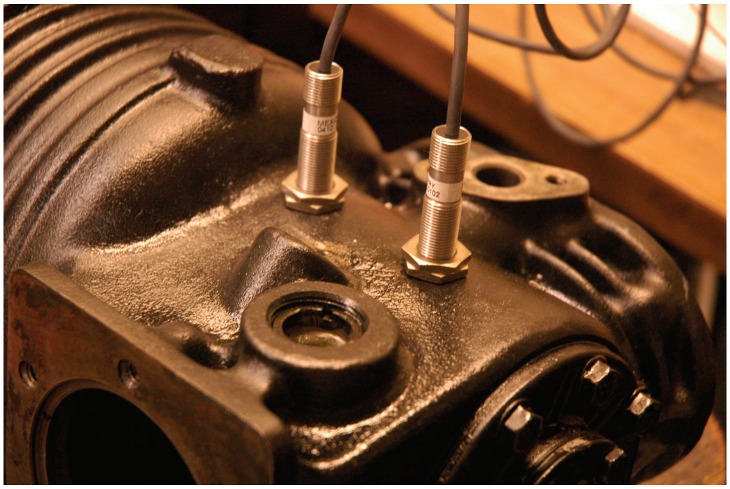

Figure 3: Picture of installation of position sensors.

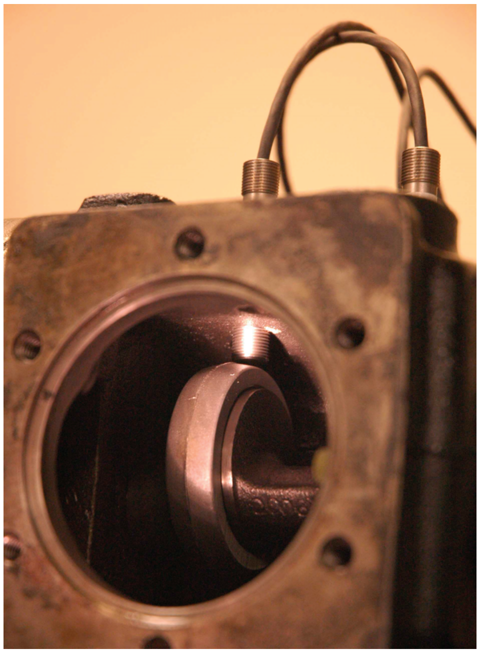

Figure 4: Closeup picture of position sensors.

briefly describe the compressor: the cylinder diameter is 1.353 inches, the stroke is 0.916 inches, the suction port diameter is 0.421 inches, and the discharge port diameter is 0.373 inches. These measurements suggest that, in the absence of extremely large amounts of liquid, it will be difficult to damage the compressor through slugging, since the area of the discharge port is more than 16% of the cylinder bore. In some senses, this is a good compressor on which liquid slugging detection strategies can be tested; if slugging can be detected in this compressor, it should be easily detectable on other larger compressors.

In order to characterize the liquid slugging behavior, two different sets of mechanical measurements were obtained: a set of two measurements of the crankshaft position, and a set of four pressure measurements. The position of the pistons was measured by fitting the compressor with two geartooth sensors manufactured by Cherry Corp. in order to identify the passage of the connecting rods past the face of the sensor. Each geartooth sensor was mounted by drilling one hole in the side of the compressor in the plane of each connecting rod so that the sensor could be screwed in and adjusted to the appropriate depth. Since the connecting rods on this compressor were made out of aluminum, a tiny hole was also drilled halfway into each connecting rod and a steel set screw was fixed into each to enable the geartooth sensor to identify the position of the piston. The distance of the face of each sensor from the connecting rod was visually adjusted until each sensor output was consistent, and then the sensors were mechanically fixed in place and sealed with Loctite. This setup is illustrated in Figures 3 and 4.

Figure 3 illustrates the location of the two geartooth sensors in the side of the compressor. In this picture, the compressor has been laid on its side, so that the bottom of the compressor is at the bottom left-hand corner of the picture. The precise location of the position sensors can be seen more clearly in Figure 4, which shows the view looking inside the compressor through the hole located in its base. The crankshaft and connecting rod are both visible here, as well as a portion of the position sensor inside the compressor shell, located right above the connecting rod. The crankshaft is rotated into a position that made it possible to situate the position sensor precisely to both prevent it from colliding with the connecting rod and also maximize its sensitivity to position.

These position sensors can also be used to measure the rotational speed of the compressor shaft. Since the number of samples between consecutive edges of the geartooth sensor waveform is directly related to the shaft speed, a processing method can be developed that can identify changes in the shaft speed due to a liquid slugging event. The output waveform is somewhat noisy, due to jitter in the timing of the edges, but the behavior of the underlying speed signal

Figure 5: Picture of modified head for pressure instrumentation and slugging apparatus.

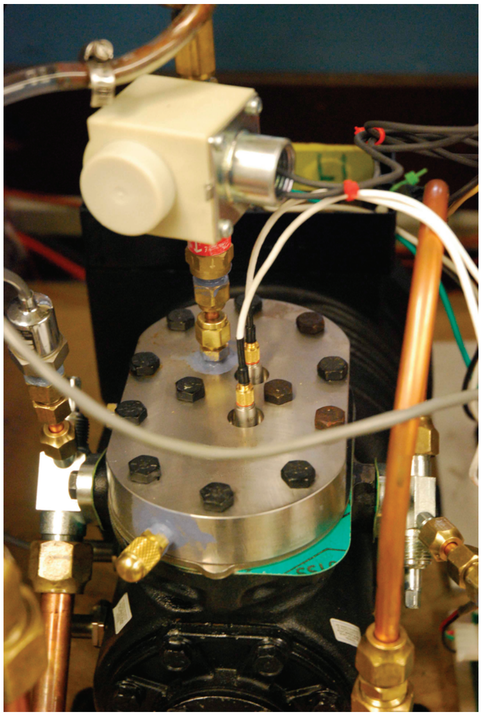

Figure 6: Picture of fully instrumented compressor.

can be obtained by filtering the output. A wavelet filter bank was also used for this purpose, due to the structured nature of the noise.

Four different pressure measurements were used to identify liquid slugging faults: the pressure in each cylinder was measured directly, and the pressures at the suction and discharge ports of the compressor were also measured so that the cylinder pressure readings could be correlated with both the compressor power and the additional pressure measurements. The measurement of the suction and discharge pressures were relatively easy to obtain, as the sensors could be directly attached to the service valves. The sensors used for this purpose, manufactured by Measurement Specialties, Inc., were calibrated appropriately for the expected maximum pressure in their respective locations.

A new compressor head was fabricated and a factory-provided valve plate was modified to facilitate the installation of the two cylinder pressure sensors. These sensors were manufactured by Kulite, Inc., and function by measuring the deflection of a calibrated strain gauge located at the tip of the sensor face. The custom head, as illustrated in Figure 5, was designed to position the two cylinder pressure sensors so that the face of the sensor was flush with the bottom of the modified valve plate, which had holes added to allow the pressure sensors to pass through. The two small installation holes for the pressure sensors are visible in the dividing wall between the suction and the discharge chambers in the center of the head in Figure 5. While these holes in the valve plate will increase leakage past the valves and reduce the efficiency of the compressor, this effect was minimized by making the clearance in the holes as small as possible. Moreover, this effect can be tolerated due to the fact that the objective of these experiments is only to correlate the overpressures caused by liquid slugging with changes in the electrical power; if the slugging-induced overpressures are lower in this experiment than they would be in an unmodified compressor, the performance of the fault detection method will improve when used on field-installed equipment.

The fabrication of a new custom head was also useful because it made it possible to locate the liquid injection port directly above the suction reed valve of one of the cylinders. This liquid injection port is visible in the top left corner of the suction chamber (on the right side of the head) in Figure 5. A small water-cooled reservoir of liquid refrigerant, fed by the liquid line of the air-conditioning unit, was used to supply the liquid slugs. This reservoir was located above a solenoid valve which was connected directly to the liquid injection port. A length of copper tube also extended down into the head so that the liquid could be deposited directly above the suction valve. The liquid was not deposited directly in the cylinder because the length of tube needed would have substantially increased the clearance volume of the cylinder. Such an effect would dramatically affect the compressor's performance and significantly change the relation between the slug mass and the magnitude of the pressure response.

The general layout of the experimental rig largely resembles the setup discussed in (Laughman *et al.*, 2006), while the particular configuration of the liquid injection apparatus and pressure sensors can be seen in Figure 6. The two cylinder pressure sensors are visible in the center of the compressor head, as is the liquid injection apparatus and solenoid valve (the large white box in the picture) that extends vertically above the head. The solenoid valve is activated by a solid-state relay, which is in turn controlled by a microcontroller-based system, allowing for the precise specification of the timing and quantity of liquid injected into the compressor head. As has also been noted by Singh *et al.* (1986), the precise measurement of the quantity of liquid entering the cylinder in a given cycle is quite difficult to ascertain; measurements of the cylinder pressure will indicate that liquid is present in the cylinder, but not the exact quantity of liquid. Moreover, one can see from the close proximity of both of the suction ports in Figure 5 that the configuration of this particular experimental setup ensures that some of the liquid injected will enter both cylinders in a given crankshaft rotation, while the remainder of the liquid will remain in the suction chamber and either evaporate or be ingested in subsequent rotations. The quantity of liquid ingested into the cylinder was controlled by varying the amount of liquid injected into the head, as the presence of more liquid in the head increases the likelihood that more liquid will be ingested into the cylinder. This liquid supply was modulated by changing the duration of time that the solenoid valve was kept open.

Electrical instrumentation make up the remaining components in the sensor network needed to validate this liquid slugging detection method. One voltage transducer and one current transducer, both manufactured by LEM, Inc., were used to monitor each of the three phases of the compressor motor. All of the sensor signals were then processed by custom-built amplifiers and collected by a USB-based data acquisition system, also built at MIT for the purposes of this experiment. This data acquisition system, as well as the control system for the solenoid valve, was interfaced to a 800 MHz PC running Debian Linux, which could simultaneously collect data from all of the sensors. Such a system was essential to the success of this experiment, as 12 channels of data had to be sampled at frequencies at or above 8 kHz.

4 RESULTS

Once the suite of instrumentation was installed, several liquid slugging experiments were conducted to test the accuracy and sensitivity of the liquid slugging fault detection method. After running the compressor for a sufficient period of time to allow the motor to reach thermal equilibrium, the solenoid valve was opened for a specified interval to inject a controlled quantity of liquid into the cylinder. While it was clear that liquid refrigerant entered both cylinders because of the increase in both of the cylinder pressures, the oil present in the mixture of oil and liquid refrigerant injected into the rear cylinder (over which the injection apparatus was positioned) caused the suction reed valve for that cylinder to behave poorly during the slugging event. This behavior was characterized by negative pressure spikes during the suction part of the stroke caused by increased stiction between the valve and the valve seat due to the additional oil on the reed valve. This oil was largely deposited on the rear suction valve, however, allowing the front cylinder to behave normally; the pressure waveforms from the front cylinder during the liquid slugging events therefore illustrate the overpressures more clearly, and will be presented in this section.

In the first set of experiments illustrated in Figures 7 and 8, the solenoid valve was opened for 133 ms while the compressor was operating in steady-state. The currents i_{ds} and i_{qs} into the compressor motor during this liquid slug are illustrated in Figure 7. One can visibly identify the change in both the d-axis stator current and the q-axis stator current during the slugging event, which is consistent with the expectation that both will change during a temporary deviation in the torque produced by the compressor motor. It is notable that the change in the d-axis current is much larger than the change in the q-axis current, making the d-axis current more useful for constructing a fault diagnostic metric. One formulation of such a metric is suggested by the bottom plot in Figure 7, which shows the results of

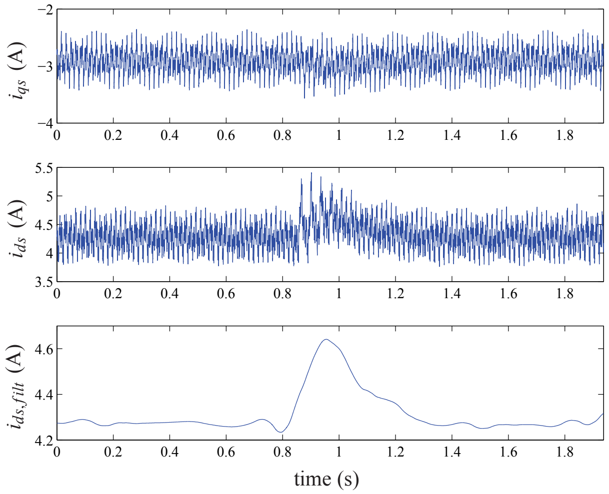

Figure 7: i_{ds} and i_{qs} for the compressor during the ingestion of a 133 ms liquid slug, as well as a filtered version of i_{ds} which could be used for a fault detection algorithm.

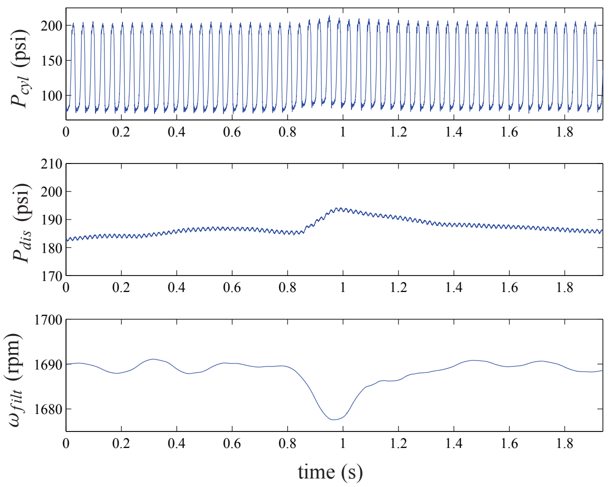

Figure 8: The front cylinder pressure P_{cyl}, the discharge pressure P_{dis}, and the filtered compressor speed ω_{filt} during a 133 ms liquid slug.

processing the d-axis current with a wavelet filter bank, and reconstructing the approximation coefficients of the signal. A simple change-of-mean detector based upon this signal could be implemented to identify the occurrence of liquid slugging.

In order to verify that the changes in the compressor power are caused by liquid slugging, the front cylinder pressure P_{cyl}, the pressure at the discharge port service valve P_{dis} and the shaft speed ω_{filt} are illustrated in Figure 8. There is clearly a small pressure rise in the cylinder pressure during the slugging event, as liquid is ingested into the cylinder. While such a small pressure increase might not be initially expected, the small cylinder bore and the comparatively large size of the discharge port suggest that it is not difficult for the piston to clear all of the liquid out of the cylinder. This would clearly not be the case with a much larger machine; other research (Singh *et al.*, 1986) has shown that much higher pressures can result in larger machines, and these would be even more detectable in the current waveforms. These cylinder pressures are further corroborated by the measurements of P_{dis}, which match the time variations of the cylinder pressure extremely well. While such a rise in P_{dis} might not be initially expected, the surplus refrigerant which exits the discharge port of the cylinder will evaporate as it leaves the compressor, resulting in this pressure spike. Finally, the plot at the bottom of this figure shows that the ingestion of this quantity of liquid also causes the speed to drop by approximately 10 rpm, after which it gradually recovers as the cylinder and discharge pressures return to normal.

As a liquid slugging detection method should identify both the presence and the quantity of liquid ingested by the compressor, a second set of liquid slugging data was obtained by injecting a large quantity of liquid into the compressor head. The effects of this larger slug, during which the solenoid valve was opened for 533 ms, are illustrated in Figures 9 and 10. While these plots are qualitatively similar to the previous data which has been presented, it is clear that the larger slug has the expected effects on the observed variables. A much larger change in both i_{ds} and i_{qs} is visible, and the effect of the larger slug on the filtered output $i_{ds,filt}$ is even more dramatic. Turning to the observed mechanical variables, the rise in P_{dis} is at least twice as large as it was for the smaller liquid slug, and there is a comparable change in P_{cyl}. One can also notice a dramatic drop in the speed of the compressor, as the speed is reduced by nearly 30 rpm during the slugging event.

5 DISCUSSION

The results shown above demonstrate that observations of the power can be very effective in identifying liquid slugging-induced overpressures in reciprocating compressors. Moreover, these results are particularly interesting

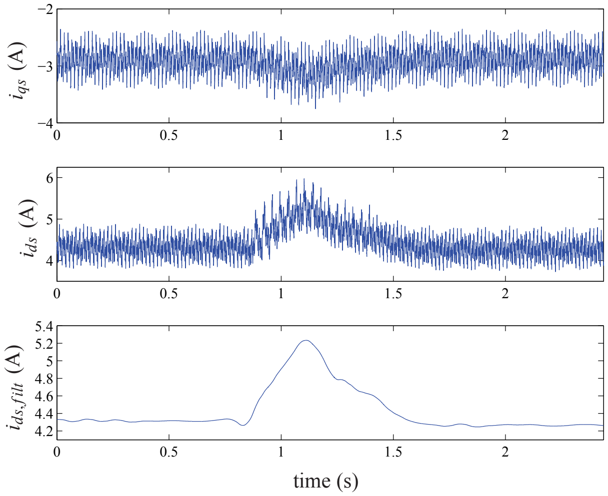

Figure 9: i_{ds} and i_{qs} for the compressor during the ingestion of a 533 ms liquid slug, as well as a filtered version of i_{ds} which could be used for a fault detection algorithm.

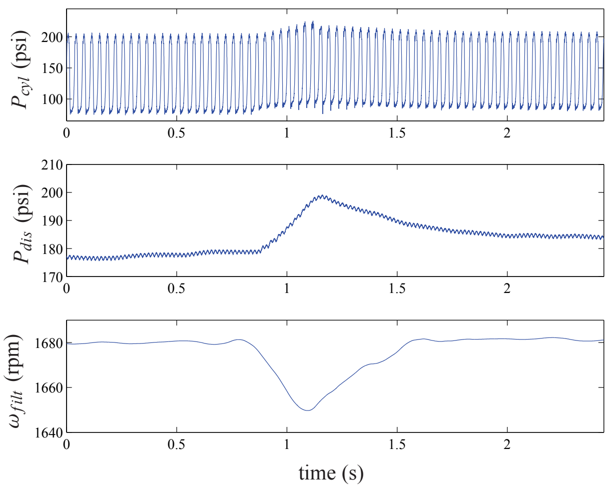

Figure 10: The front cylinder pressure P_{cyl}, the discharge pressure P_{dis}, and the filtered compressor speed ω_{filt} during a 533 ms liquid slug.

because the quantities of liquid ingested by the compressor during these tests neither damaged the compressor nor affected the system performance beyond the duration of the liquid slugging event. This fact, as well as the fact that these experiments were carried out on semi-hermetic compressor connected to a commercially available evaporator and condenser of a size often used in a residential setting, suggests that there is great potential in the use of electrical measurements to identify mechanical faults in compressors in a field setting. Further investigation of such fault detection techniques, in all types of compressors, may yield new and sensitive methods for providing technicians and service companies with the means to quickly identify and locate faults before irreparable damage is caused to the compressor, without the need for expensive and delicate mechanical transducers.

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