Multidisciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P12453

Developing, Installing and Validating Health-Monitoring Capabilities on a Reciprocating Compressor at the Rochester Institute of Technology

Markus Holzenkamp
(ME)

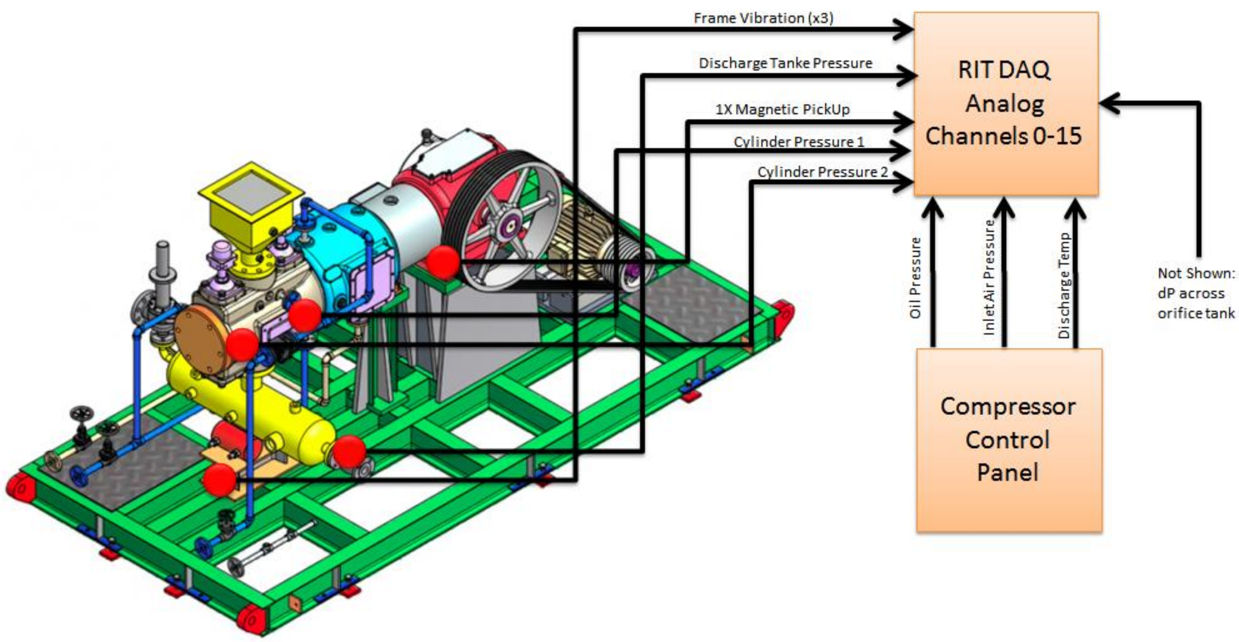
Cody Anderson
(ME)

Robin Leili-Marrazzo
(ME)

Abstract

The main goal of Senior Design Project P12453 was to expand the data acquisition capabilities on a reciprocating compressor in order to provide condition monitoring, also known as health monitoring.

Our starting point consisted of the installed compressor with cylinder pressure and vibration sensors. We decided on additional sensors, selected which model of sensors we needed and where best to install them to get accurate results. The data acquisition system was also rewired to eliminate signal noise issues. RIT now has the capabilities to measure various condition indicating parameters of the compressor. This includes the temperature of the crankshaft bearings, the current drawn by the motor, the temperature of the discharge air as well as the temperatures at all critical points in the cooling system. We can also create an operating pressure-volume diagram with the cylinder pressure transducers and an incremental encoder which measures crankshaft position.



Project Requirements and Background

Dresser-Rand (DR), a global company specializing in reciprocating and turbo-machinery in the energy sector, donated the reciprocating compressor as part of a university relations program and previous senior design projects dealt with its installation. Group P09452 prepared the room for the installation and developed a simulation of the compressor. The next group, P11452, took delivery of and installed the compressor at the Rochester Institute of Technology (RIT). This group also installed the first sensors on the compressor and took a couple measurements to get a basic understanding of the operating characteristics. After this, a summer co-op student installed a more capable data acquisition system in the compressor lab, featuring a National Instruments 8 –bay chassis (NI-DAQmx) along with a 32 channel analog-in module (NI 9205) and a 16 channel thermocouple module (NI 9213).

For this senior design project, DR also donated their Envision condition monitoring system, which represents their current state of health-monitoring systems. As part of this project, we were to install this system along with the required sensors. Additionally, we were to install several more sensors that would allow us to monitor details about the cooling system of the compressor. However, due to time delays out of our control we did not receive the Envision system until a week before this project ended. The system will be installed either by a later senior design group or by students performing research on the compressor.

In summary, the customer requirements for this project were:

1. Increase the capabilities of the RIT developed data acquisition system. This includes specifying and implementing, additional sensors and a robust LabView interface to allow for data collection.
2. Install the DR Envision system.
3. Develop possible undergraduate laboratory exercise to be used in RIT courses.

Health-Monitoring

An effective way to monitor reciprocating compressors is by evaluating their real time P-V diagrams. It is relatively easy to monitor pressure in the cylinder and if the crank angle can be monitored accurately, the pressure-volume relationship can be generated.

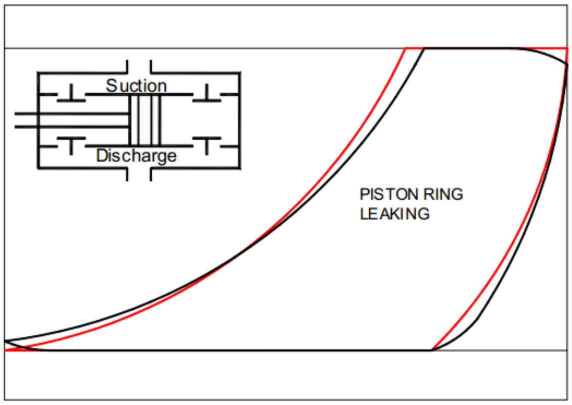


Figure 1: Difference between healthy (red) and faulty (black) P-V diagram [1]

This can then be compared to a theoretical diagram and deviations signal a part failure on the compressor [1]. Other techniques that can be used to monitor the condition of a reciprocating compressor include vibration monitoring and temperature monitoring. For vibration monitoring, two main categories should be considered: crankcase vibration and crosshead/distance piece vibration. Since most reciprocating compressors have a balanced opposing cylinder configuration, measuring the vibration of the crankcase allows the detection of any failure that would upset this inherent balance. In this case, we have a single cylinder compressor so the focus is on the crosshead vibration in the vertical axis. Measuring the vibration or acceleration of the crosshead will forecast bad needle bearings, clearance issues, and others failures that result in impact events to the crosshead. For temperature monitoring, typical measurements include cylinder discharge temperature, valve temperature, packing temperature, crosshead pin/big end bearing temperature and main bearing temperature. Cylinder discharge temperature can show leaks in rings and valves. Valve temperatures can show individual valve problems. Packing temperature can show packing leakage and bearing temperature can show a failing bearing [2]

Based on this literature and discussion with our customer Dr J. Kolodziej, we decided to measure the following parameters:

1. Temperatures throughout the cooling system
2. Coolant flow rate
3. Discharge tank pressure
4. Discharge air temperature
5. Crankshaft rotation
6. Motor current draw
7. Vibration in the x-,y-, and z-direction
8. Oil pressure
9. Oil temperature
10. Crankshaft bearing temperatures
11. Delta pressure across an orifice tank to determine air flowrate
12. Temperature at the orifice tank outlet

Concept Selection

In our pursuit to design, develop, and install effective health monitoring capabilities many different idea organizing tools were utilized. Starting with a function diagram based on customer needs we listed all parameters which needed to be measured on the compressor. Engineering specifications were developed for all of our requirements, and a weighted house of quality was used to rank each engineering specification based on its importance to fulfill customer needs.

Concept generation was considered an open team forum. When we had several ideas for each requirement a Pugh concept selection method was used. Similar to a house of quality with engineering specifications, concepts were evaluated against criteria, but all concepts are given a “plus” or “minus” compared to a datum concept. We moved forward with the concept that had the best score.

Testing potential concepts for robust design by modeling, holding design reviews with peers and specialists, and interviews with knowledgeable people in the field also helped generate new concepts and rule original concepts out. Implementing all of these results easily narrows down options and hardware capable of the particular application.

Sensor Installation

Once an installation concept and process was chosen for a given sensor and all necessary materials were received, we proceeded with installing the sensor. Some cases required more altercations or machining to complete than others. On the next page is an example which shows the modification made to the flow-sight in order to install a thermocouple probe. This thermocouple measures the overall temperature of the coolant as it leaves the compressor.

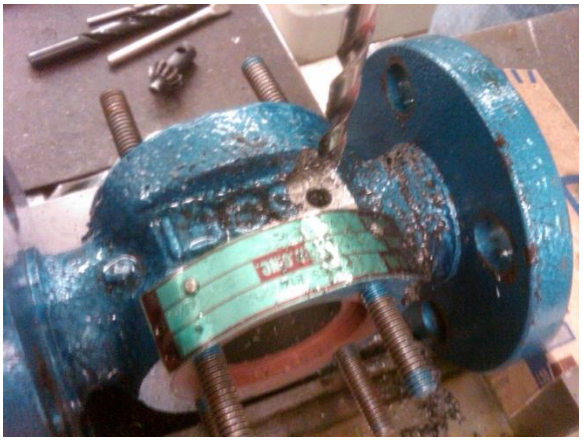


Figure 2: Example of modifications to existing structure necessary to accommodate sensor installation

Most sensors had less complex installations. For measuring the head end coolant temperature and the cylinder wall coolant temperature pre-existing ports in the compressor's housing could be used. Making use of the existing structure as often as possible reduced the complexity of our designs and increased robustness. The other sensors that required major modification to the compressor were the crankshaft bearing temperature probes, which were installed by Dresser-Rand technicians. Dual floating, journal bearings are used in the ESH-1, therefore drilling through the casing is a high risk operation without part drawings and previous experience. The holes for the thermocouples in casing had to be deep enough to get the probes as close to the bearing as possible without breaking through and allowing oil to leak. Below is a picture of the installed thermocouple probes. Two fittings are used to seal the probe's access, one at the tip to hold the probe close to the bearing and another fitting in the crankcase's outer wall for sealing as oil splashes in the crankcase and to fasten the probe in position.

Figure 3: Installed crankshaft bearing thermocouple probe

We would like to thank Scott Delmotte and Steve Deming from Dresser-Rand in Painted Post, New York for coming to RIT and performing the install of these sensors.

Data Acquisition

60 Hz Signal Noise

One of the initial concerns with the RIT DAQ was a consistent 60 Hz signal noise recorded on all channels. The noise was sensor independent and was also recorded when no sensors were connected. As time passed the signal to noise ratio increased and began to spread across channels. The source of the noise was improper grounding of the independent channels in the pre-existing DAQ. The power in the compressor room was on the same circuit as the machine shop. As such all of the equipment was grounded together and noise generated by the mills, lathes and all other machinery was picked up across their universal ground. Any sensors which required their own external power supply, such as the pressure sensors and flow meter, would subsequently carry with it the signal noise which was being generated over the machine shop circuit. The solution to the problem was to isolate the DAQ and all subsequent hardware from the machine shop circuit. This was done by wiring a new ground for the compressor room equipment. Once the new grounding was implemented the powered inputs no longer showed the large 60 Hz interference through the DAQ.

Channel Cross-talk

After the initial signal noise issue was solved a smaller amount of interference was still present. While the large 60 Hz noise was gone, there was extensive cross talk going on between the various channels of the DAQ as well as a time dependent signal which would grow first on the higher channels and then on the lower ones. After examining the wiring of the individual channels of the DAQ it was apparent that each of the inputs was not properly grounded. This prevented the DAQ from getting an accurate reference voltage which it could use to scale the inputs it received. Each of the channels signal grounds were then wired across to a common ground. This greatly decreased the signal to noise ratio.

DAQ Layout

In order to most effectively deal with the large number of sensors connected to the DAQ, four specialized LabView programs were created. The first two programs, or Visual Interfaces (VIs), allowed for highly configurable data collection. One VI was created for dealing with analog channels and the second one specifically for thermocouple channels. The user is able to specify the desired channel(s), sample rate, number of samples, and the appropriate conversion factors. A graph gives a visual confirmation of the data collected. Below are screenshots of the front panels of both VIs. Also included on the front panel is a table with channel assignments and necessary conversion factors.

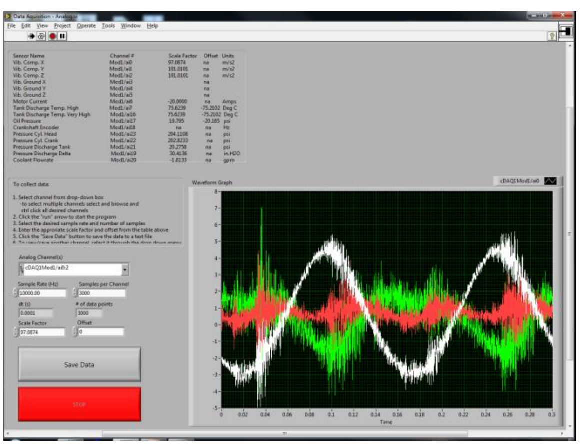


Figure 4: Analog channel data collection

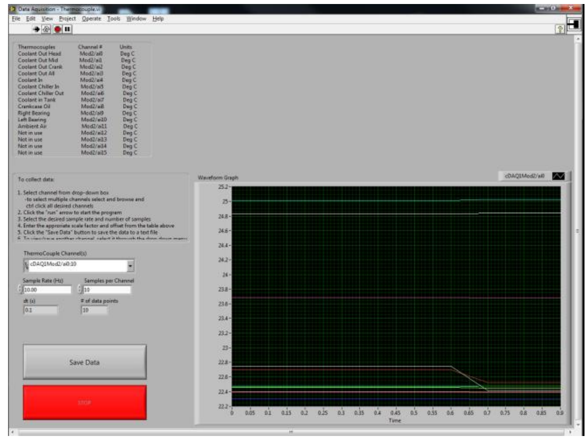


Figure 5: Thermocouple channel data collection

The third VI serves as a general monitoring platform where all sensor data is shown to the user. Graphs were chosen over numerical indicators to make it easier to notice trends over time. For pressure, current, and flow-rate measurements, traditional gauge displayed with numerical indicators were used to combine the visual familiarity of analog gauges with high precision measurements. Additionally, this VI allows the user to create a save file with data from every channel. However, since such a vast amount of data is collected, this VI lacks some of the desirable fine tuning options of the other interfaces. Lastly, a separate VI was created to generate P-V diagrams. This VI had to be constructed separately because each measurement has to reference the encoder for its timing. This serves to line up pressure measurements with the correct volume. The program counts the digital edges returned by the encoder as it turns with the crankshaft and uses this measurement to determine the current angle of the crankshaft. Then, since the dimensions of the stroke and radius are known, volume is calculated. By plotting this and the pressure measured by the in-cylinder pressure sensors on a xy-plot, a live P-V diagram is created. For all four VIs, the voltage measured by the DAQ had to be converted into appropriate engineering units. In some cases, the conversion factor was included on the calibration specification sheet of the sensor. In other cases, it was experimentally determined by taking point measurements of the voltage and the displayed value in the desired units and creating a line fit to determine the conversion factor. A list of all conversions was included in the appendix.

Current to Voltage

The flow meter, discharge tank pressure sensor, and the delta pressure sensor, and cylinder pressures are powered sensors. This means they require a constant power source to operate. The signal is transmitted by the current through the power wire. The RIT DAQ only contains a voltage module, so in order to monitor these sensors, a resistor was placed in line on the negative wire and the voltage difference across the resistor was then monitored by the DAQ. Given the known operating range of 4-20 mA for the sensors and the known resistance of 250Ω, a proportional voltage measurement could be made.

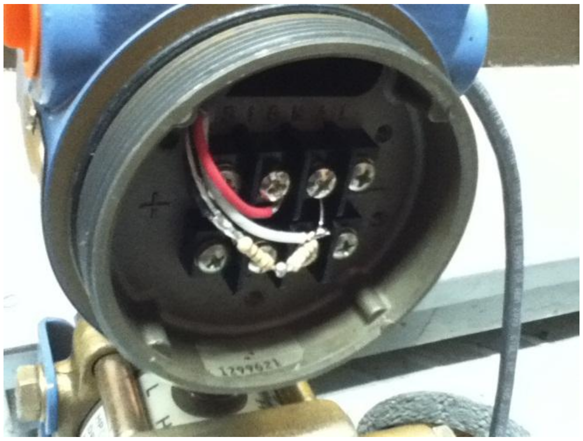


Figure 6: Resistor in line with 4-20ma output to get a voltage signal

Base line readings

Once all the sensors were operational, data was collected. We recorded temperatures from the thermocouples over the course of one hour, with a reading taken every ten minutes. The resulting plot is shown below.

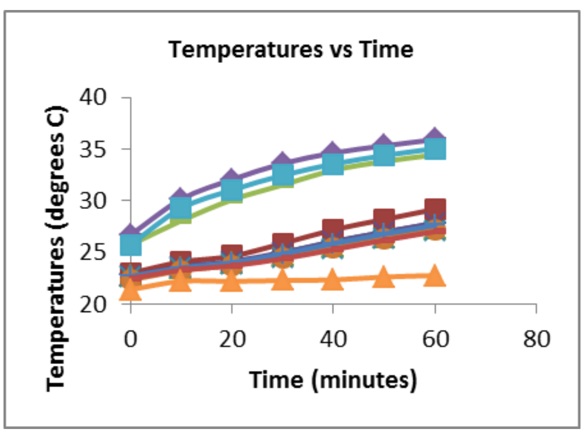


Figure 7: Thermocouple data over one hour

Additionally, a steady-state reading of the analog channels was taken at 0%, 50%, and 100% compressor load.

Sensor	0%	50%	100%
Current (Amp)	5.86	6.55	8.36
Coolant Flow (gpm)	7.99	8.02	7.97
Oil Pressure (psi)	30.73	29.78	29.30
Discharge Temperature High (deg C)	22.83	24.32	28.83
Discharge Temperature Very High (deg C)	21.97	24.99	32.82

Table 1: Sensor readings at the various compressor loads

This data was collected in addition to the vibration data and in-cylinder pressure data for which the previous group installed the sensors. However, instead of using a temporary DAQ device, these sensors are now connected to the permanent NI-DAQmx.

By using an incremental encoder to measure crank angle and the in-cylinder pressure sensors we can create an actual P-V diagram of the compressor.

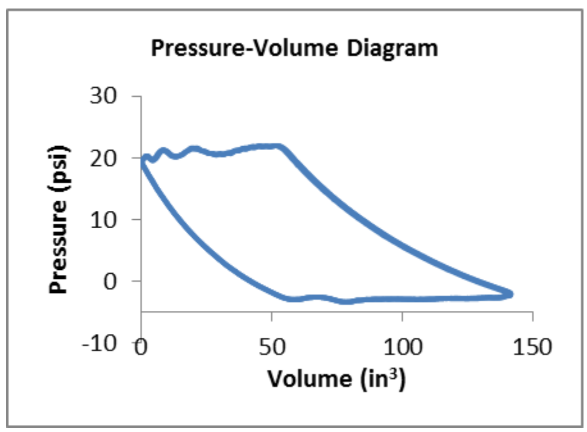


Figure 8: P-V Diagram of the compressor

In order to synchronize the pressure measurements with the angle measurements from the encoder, the encoder channel A is used as an external clock for the data acquisition. Also, to create a true P-V diagram, the instantaneous in-cylinder volume has to be calculated in terms of crank angle. This is can be done if the dimensions of the piston assembly are known.

Below is a simplified sketch of the crankshaft, connecting rod, and piston.

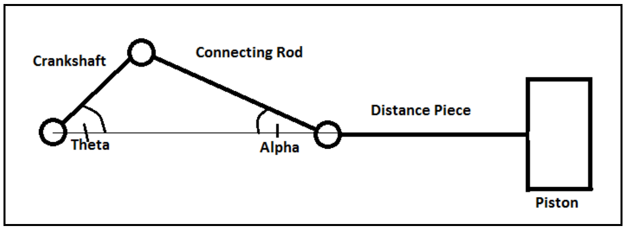


Figure 9: Piston Assembly

Since the crankshaft radius and the length of the connecting rod are known, the angle α can be calculated in terms of θ, which is measured by the encoder. The following equation was then used to calculate the instantaneous volume of the cylinder.

$$V = \pi r_{equivalent}^2 * L_{cylinder}$$

Equation 1: Instantaneous cylinder volume

Where $r_{equivalent}$ is calculated with the known air flowrate, stroke of the piston, and operating speed. Using the equivalent radius allows for the modelling of the compressor cylinder as a perfect geometric cylinder. The instantaneous cylinder length, $L_{cylinder}$, is calculated from the measured angle as follows.

$$L_{cylinder} = [L_{crank} + L_{connecting\ Rod}\ ] - [L_{crank}\cos(\theta) + L_{connecting\ Rod}\cos(\alpha)]$$

Equation 2: Instantaneous cylinder length

Finally, α is calculated from θ.

$$\frac{\sin(\alpha)}{L_{crank}} = \frac{\sin(\theta)}{L_{connecting\ Rod}}$$

Equation 3: Calculating alpha

We took a measurement from all channels as a means of establishing a base line for all available outputs. During the life of the compressor, the performance as well as the condition of components will begin to deteriorate. By comparing sensor data to a base line values from when the compressor was new, valve-wear, bearing-fatigue, and other mechanical failures can be determined.

Summary of Results

As a result of this senior design project, we are able to monitor the vibration of the compressor in three dimensions, the pressure both in-cylinder and in the discharge tank, the current drawn by the electric motor, the position of the crankshaft as well as its rotational velocity. Several thermocouples were introduced into the cooling system to monitor temperatures at the inlet, the head-, cylinder-, and crank-side outlets as well as after these three combine. Additional measurements were made before and after a heat-exchanger and in the reservoir tank. We are also able to monitor the temperature in the air discharge tank as well as crankshaft bearing temperature, oil temperature and pressure. The VIs created in LabView allow the user to save data from each channel at a user-specified sampling rate and number of samples, a live pressure-volume diagram can be shown and monitored by the user. Lastly, a central VI allows for the monitoring of all characteristics of the compressor.

Comments and Conclusions

This project provided all of us on the team a great learning experience in the world of data collection and sensor technology. Having someone on the team who was more familiar with the electronics side would have proved useful. Various issues with wiring sensors correctly, grounding, and eliminating noise in the signal proved to be among the greatest challenges. This project also demonstrated how important communication between all parties is. It became clear to us early in the project that DRs Envision system would be delayed and that the customer needs and requirements had to be revised to account for this. Overall, this project was a success as it provides a solid base that allows further research into reciprocating compressor health-monitoring and as such fulfills the main objective we set out to complete.

References

[1] Diab, S., and Howard, B., "Reciprocating Compressor Management Systems Provide Solid Return on Investment."

[2] Schultheis, S. M., Lickteig, C. A., and Parchewsky, R., 2007, "Reciprocating Compressor Condition Monitoring," Proc. Turbomachinery Symposium, pp. 107-113.

Appendix A – DAQ Channel Assignments

Table A-1: Channel assignment with conversion factors for Analog-in (NI 9205)

Sensor Name	Channel #	Scale Factor	Offset	Units
Vib. Comp. X	Mod1/ai0	97.0874	na	m/s2
Vib. Comp. Y	Mod1/ai1	101.0101	na	m/s2
Vib. Comp. Z	Mod1/ai2	101.0101	na	m/s2
Vib. Ground X	Mod1/ai3	na	na	na
Vib. Ground Y	Mod1/ai4	na	na	na
Vib. Ground Z	Mod1/ai5	na	na	na
Motor Current	Mod1/ai6	-20.0000	na	Amps
Tank Dis. Temp. High	Mod1/ai7	75.6239	-75.2102	psi
Tank Dis. Temp. Very High	Mod1/ai16	75.6239	-75.2102	psi
Oil Pressure	Mod1/ai17	19.975	-20.185	psi
Crankshaft Encoder Frequency	Mod1/ai18	na	na	Hz
Pressure Cyl. Head	Mod1/ai23	20.41108	na	psi
Pressure Cyl. Crank	Mod1/ai22	20.28233	na	psi
Pressure Discharge Tank	Mod1/ai21	20.2758	na	psi
Pressure Discharge Delta	Mod1/ai19	30.4136	na	in.H2O
Coolant Flowrate	Mod1/ai20	-2.0340	na	gpm