INDUSTRIAL ENGINE RELIABILITY AND MAINTENANCE – DATA THAT SHOULD BE COLLECTED AND ANALYZED ON EVERY ENGINE

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ABSTRACT

This paper discusses the steps involved in developing a good monitoring plan for a reciprocating engine. Each step is discussed in detail, finishing with a case study illustrating the failure of a reciprocating engine component.

1. INTRODUCTION TO ENGINE RELIABILITY AND MAINTENANCE

Industries that use reciprocating internal combustion engines to drive compression equipment need their equipment to be reliable. This need stems from well known costs of lost production and down time. Many internal combustion engine units are upstream of other critical process equipment; thus if the engine is unreliable, equipment downstream can be seriously affected.

Maintenance is needed to keep the engine reliable and ensure it is performing to the level required. Over time, without regular maintenance, engines can suffer reduced horsepower capacity and fuel efficiency. This degraded condition can lead to unexpected engine overloading and many reliability and maintenance issues.

Like most machinery, engine component failures can range from quick, relatively cheap fixes to very expensive, time intensive repairs. Most engine component failures render the engine inoperable. Many, if not most, engine component problems generate condition indicators that provide early warning of potential failures. If these condition indicators are monitored properly, failures can be avoided minimizing costly down time.

Traditionally, maintenance philosophies involve performing overhauls after set time intervals; usually after a fixed value of running hours for an engine. These overhauls are very expensive and guarantee a certain level of downtime for each time interval. The overhauls are performed whether a unit needs it or not. A condition monitoring philosophy allows maintenance to be scheduled when the need arises. This, when implemented well, leads to capital savings, increased engine availability, and less maintenance.

Reciprocating engines come in many variations, but in today's industry engines are generally categorized as four stroke, two stroke, natural gas fueled, gasoline fueled, or diesel fueled.

2. DEVELOPING A MONITORING PLAN FOR AN ENGINE

2.1. Four steps are needed to develop a good monitoring plan:

a. Define the failure modes of the engine.
b. Identify condition indicators for each failure mode.
c. Develop a monitoring plan to produce the condition indicators.
d. Act on the findings of the monitoring plan.

The details of these four steps in terms of reciprocating internal combustion engines are described in the following section.

2.2 Define the Failure Modes of an Engine

What is meant by failure modes? In the context of this paper, a failure mode refers to the following three characteristics:

a. Something that prevents the engine from operating (e.g., broken parts).
b. Degradation that prevents an engine from meeting its rated performance requirements.
c. Operation that accelerates the wear on the engine, thus dramatically reducing its operating life span.

An engine is made up of components, each of which is integral to the operation of the engine. To define the failure modes of an engine, a definition of the failure modes of its components is needed. Table 1, though by no means complete, illustrates many common components of an engine and likely failure modes of each component.

Knowing the failure modes of each engine component allows for analysis of evidence presented by condition indicators, to keep failures from occurring.

Table 1 –Engine Components and Associated Failure Modes

Component	Sub-Component	Failure Modes								
		Leaking	Excessive Wear	Improper Lubrication and Oil Degradation	Debris and Excessive Deposits	Mechanical Resonance	Torsional Resonance	Detonation	Mis-alignment	Cracked, Broken, Fractured
Cylinders	Piston		☻	☻	☻			☻		☻
	Rings	☻	☻	☻	☻			☻		☻
	Liner	☻	☻	☻				☻		☻
	Head	☻	☻		☻			☻		☻
	Valves	☻	☻	☻	☻			☻		☻
	Ports		☻	☻	☻			☻		
Bearings	Mains		☻	☻					☻	☻
	Conrod		☻	☻				☻		☻
	Wrist pins		☻	☻				☻		☻
Pumps	Jacket Water	☻	☻	☻	☻		☻			☻
	Oil	☻	☻	☻	☻		☻			☻
Turbos/Blowers	Impeller	☻	☻	☻	☻			☻		☻
	Bearings		☻	☻				☻		☻
	Case	☻	☻		☻	☻		☻		☻
Foundation	Pedestal		☻			☻			☻	☻
	Anchor Bolts		☻			☻			☻	☻
Frame						☻	☻		☻	☻
Crankshaft			☻	☻			☻		☻	☻
Air Intake		☻			☻	☻				☻
Exhaust		☻			☻	☻		☻		☻
Ignition System			☻		☻		☻			☻
Viscous Damper		☻	☻	☻			☻			☻
Oil Filters			☻		☻					☻
Cooler/Heat Exchanger		☻			☻	☻				☻

2.3 Identify Condition Indicators for each Failure Mode

Condition indicators can be generated from engine measurements such as oil pressure, exhaust temperatures, coolant temperature, etc. Through the processes of data reduction, analysis, and trending, condition indicators can be produced to provide early warning of degradation to mechanical condition and performance. Analysis of condition indicator trends can also lead to unforeseen process improvements, adding efficiency and/or profitability to a system.

Condition indicators are often generated from measurements taken while an engine is *in operation* and can exist as real time trends for analysis. For example, Table 2 illustrates two failure modes and the associated appropriate running measurements for engine bearings and cylinders.

Table 2 – Component Failure Modes and Associated Measurement Parameters Examples

Component	Failure Modes	Engine Running Measurement Parameters											
		Timing	Oil Pressure	Oil Temp-erature	Oil Sample	Oil Flow	Coolant Temperature	Intake Manifold Pressure	Intake Manifold Temp	Exhaust Temp-erature	Fuel Flow	Vibration	Cylinder Pressures
Main, Connecting Rod & Wrist Pin Bearings	Excessive Wear		☻	☻	☻	☻						☻	
Cylinders	Detonation	☻		☻			☻	☻	☻	☻	☻	☻	☻

Notice in Table 2, each failure mode requires different measurement parameters. Since the failure mode for each component requires its own set of measurement parameters, it is very important to collect a complete set of measurements to allow for complete analysis. Table 3 shows two condition indicators that can be generated for the failure mode of excessive engine bearing wear (first row of Table 2).

Table 3 –Two Condition Indicators Generated for Excessive Engine Bearing Wear

Component	Failure Mode	Condition Indicators	
Main, Connecting Rod, & Wrist Pin Bearings	Excessive Wear	**Oil Analysis** generated from the oil sample	**Oil Filter Differential Pressure** generated from an oil pressure gauge on either side of the oil filter

In Table 3 the condition indicators of Oil Analysis and Oil Filter Differential Pressure can provide early warning for the failure mode of excessive wear on engine bearings. The measurement parameter of "Oil Sample", from Table 2, can be analyzed for wear metal content in the oil. Trended wear metal levels can indicate excessive bearing wear and usually indicate the progression of the level of bearing wear, based on the type of wear metals in the sample. The measurement parameter of "Oil Pressure," from Table 2, can be expanded (with appropriate hardware) to yield the Oil Filter Differential Pressure (OFDP) condition indicator in Table 3. An upward trend of the OFDP can indicate excessive wear on engine bearings due to wear particles from the worn bearings clogging the filter.

One or two condition indicators, however, are not enough to effectively track all the known failure modes. A good monitoring plan is needed accomplish this.

2.4 Develop a Monitoring Plan to Produce the Condition Indicators

The intent of a monitoring plan is to predict failures before they happen, with the goal of reducing costly down time. To predict failures before they occur, a complete set of measurement parameters must be collected and analyzed regularly. Tables 4 and 5 contain a fairly comprehensive list of common engine components and associated measurement parameters to be collected, trended, and analyzed, both with the engine in operation and with it shut down.

What is meant by *"collected and trended"*? In the context of this paper, a measurement parameter that has been "*collected*" is one that has been read, recorded, or sampled from a fully functional, suitable device for that particular parameter. The term "*trended*" refers to a measured or calculated parameter recorded regularly, along with the dates of collection, and compared with previously recorded data. An ongoing trend forms the foundation of a good monitoring plan for an engine.

A monitoring plan that utilizes an engine's condition indicators includes the following points:

a. Baseline values for each condition indicator from which all trends will be compared.
b. Regular, appropriately scheduled measurement collection intervals.
c. Appropriate condition indicator trends, or patterns that relate to known component failure modes.

Baseline values are often obtained from the condition of a component when it is new, or has just been serviced. These are not always easy to acquire – a large amount of equipment that has been in service for many years has limited information available. The result is that many baselines are set by experience. This experience can come from analysis of condition indicator values obtained during the first few months of a condition monitoring program, or can be obtained from other users of the same, or similar, equipment elsewhere in industry.

Regularly scheduled data collection is crucial to a successful monitoring plan. The schedule should be based on the criticality of the machine; the more critical the machine, the higher the frequency of collection.

A trend can be compiled for any condition indicator, as long as the underlying measurement parameters (data) are collected at regular intervals. But what makes a compiled trend of data useful? Consider the following example:

> Two measurement parameters collected on a particular engine are Jacket Water Temperature (JWT), and Engine Oil Temperature coming out of the engine to the cooler (EOT). One possibility for trending is to plot the values on a graph for each data collection date, similar to Figure 1, below. What kind of specific information does a trend of JWT or EOT provide about a particular failure mode? Perhaps a gradual rise in either JWT or EOT reveals that the engine is running hotter. Which may, in turn, mean that the cooler/heat exchanger is not performing efficiently. It may also mean that the

engine is running hotter for some other reason. The two trends provide general information that may be used for analysis, but the trend itself does not give specific information relating to a particular failure mode.

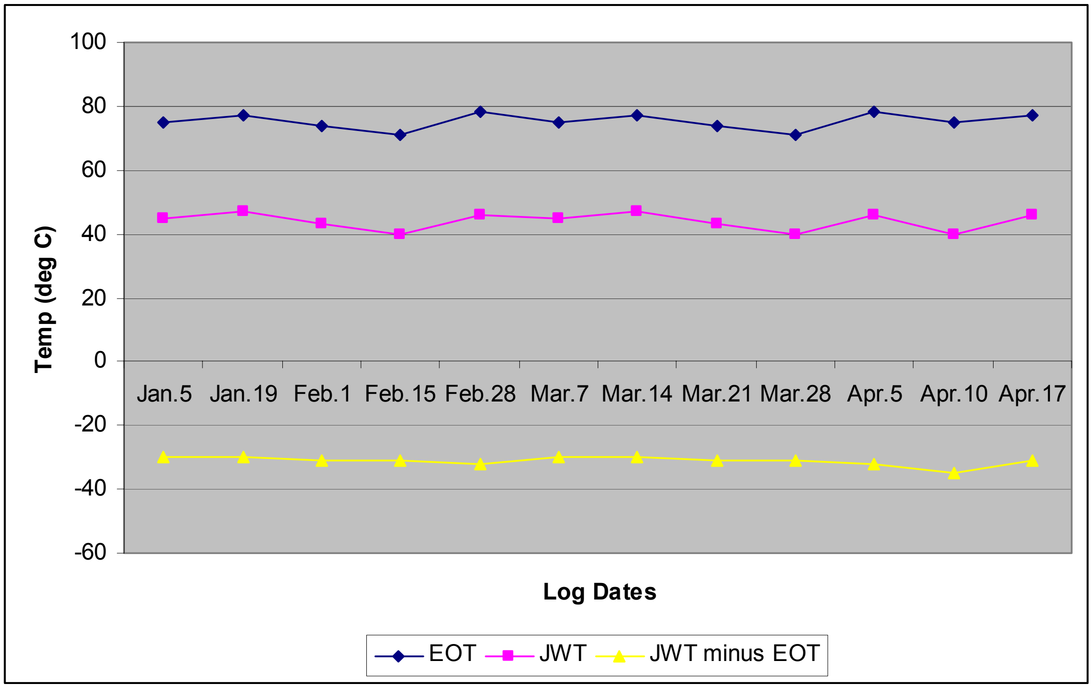


Figure 1 – Trend of Jacket Water Temperature, Engine Oil Temperature, and Jacket Water Minus Engine Oil Temperature.

The clearance between the piston and the liner in a cylinder is designed with the components at particular temperatures. The piston is cooled mostly from an oil spray underneath it, while the liner is cooled mostly by the jacket water. These components are traditionally designed for an operating temperature where the jacket water temperature is around 10 degrees above the engine oil temperature. Consider the trend of JWT minus EOT in Figure 1.

Notice that the trend is hovering consistently around the -30 degrees C mark. This is an undesirable means of operating, especially if the cylinder components were designed for a JWT of 10 degrees above the EOT. In this case, the piston will run hotter, have relatively larger thermal expansion, thus taking up more clearance between it and the liner than designed for. This can lead to the failure mode of excessive wear in the piston, rings, and liner.

Therefore, a more useful trend, such as JWT minus EOT, can be compiled to provide further, more specific, information about a failure mode.

The above example illustrates that collected and trended measurement parameters need to be applied to known failure modes to become useful condition indicators.

Table 4 – Common Engine Components and Associated Engine Running Measurement Parameters

Component	Sub-Component	Measurement Paremeters for a Running Engine																
		Speed	Timing	Oil Pressure	Oil Temp-rature	Oil Sample	Oil Flow	Coolant Pressure	Coolant Temperature	Coolant Flow	Intake Manifold Pressure	Intake Manifold Temp	Exhaust Temp-erature	Fuel Gas Regulated Pressure	Fuel Flow	Vibration	Cylinder Pressures	Crankcase Pressure
Cylinders	Piston	☻	☻	☻	☻	☻		☻	☻	☻	☻	☻	☻	☻	☻	☻	☻	☻
	Rings	☻	☻	☻	☻	☻		☻	☻	☻	☻	☻	☻	☻	☻	☻	☻	☻
	Liner	☻	☻	☻	☻	☻		☻	☻	☻	☻	☻	☻	☻	☻	☻	☻	☻
	Head	☻	☻	☻	☻	☻		☻	☻	☻	☻	☻	☻	☻	☻	☻	☻	
	Valves	☻	☻	☻	☻	☻		☻	☻	☻	☻	☻	☻	☻	☻	☻	☻	
	Ports	☻	☻			☻		☻	☻	☻	☻	☻	☻	☻	☻	☻	☻	
Bearings	Mains	☻		☻	☻	☻	☻									☻	☻	
	Conrod	☻		☻	☻	☻	☻									☻	☻	
	Wrist pins	☻		☻	☻	☻	☻									☻	☻	
Pumps	Jacket Water	☻						☻	☻	☻						☻		
	Oil Pumps	☻		☻	☻	☻	☻									☻		
Turbos/Blowers	Impeller	☻									☻	☻	☻	☻	☻	☻	☻	
	Bearings	☻		☻							☻	☻	☻	☻	☻	☻	☻	
	Case	☻									☻	☻	☻	☻	☻	☻	☻	
Foundation	Pedestal	☻														☻		
	Anchor Bolts	☻														☻		
Frame		☻		☻		☻	☻									☻	☻	
Crankshaft		☻		☻	☻	☻	☻									☻	☻	
Air Intake		☻	☻								☻	☻	☻	☻	☻	☻	☻	
Exhaust		☻	☻								☻	☻	☻	☻	☻	☻	☻	
Fuel System		☻	☻								☻	☻	☻	☻	☻	☻	☻	
Ignition System		☻	☻								☻	☻	☻	☻	☻	☻	☻	
Control System		☻	☻								☻	☻	☻	☻	☻			
Viscous Damper		☻			☻	☻										☻	☻	
Oil Filters				☻	☻	☻	☻											
Coolers/Heat Exchangers					☻	☻	☻					☻	☻			☻	☻	

Table 5 – Common Engine Components and Associated Shutdown Measurement Parameters

Component	Sub-Component	Condition Monitoring Parameters for a Stopped Engine				
		Clearances	Valve Sink	Borescope	Visual Inspection	Web Deflections
Cylinders	Piston			☻	☻	
	Rings			☻	☻	
	Liner			☻	☻	
	Head		☻	☻	☻	
	Valves		☻	☻	☻	
	Ports			☻	☻	
Bearings	Mains	☻			☻	☻
	Conrod	☻			☻	
	Wrist pins	☻			☻	
Foundation	Pedestal				☻	☻
	Anchor Bolts				☻	☻
Frame					☻	☻
Crankshaft					☻	☻
Ignition System	Spark Plugs				☻	

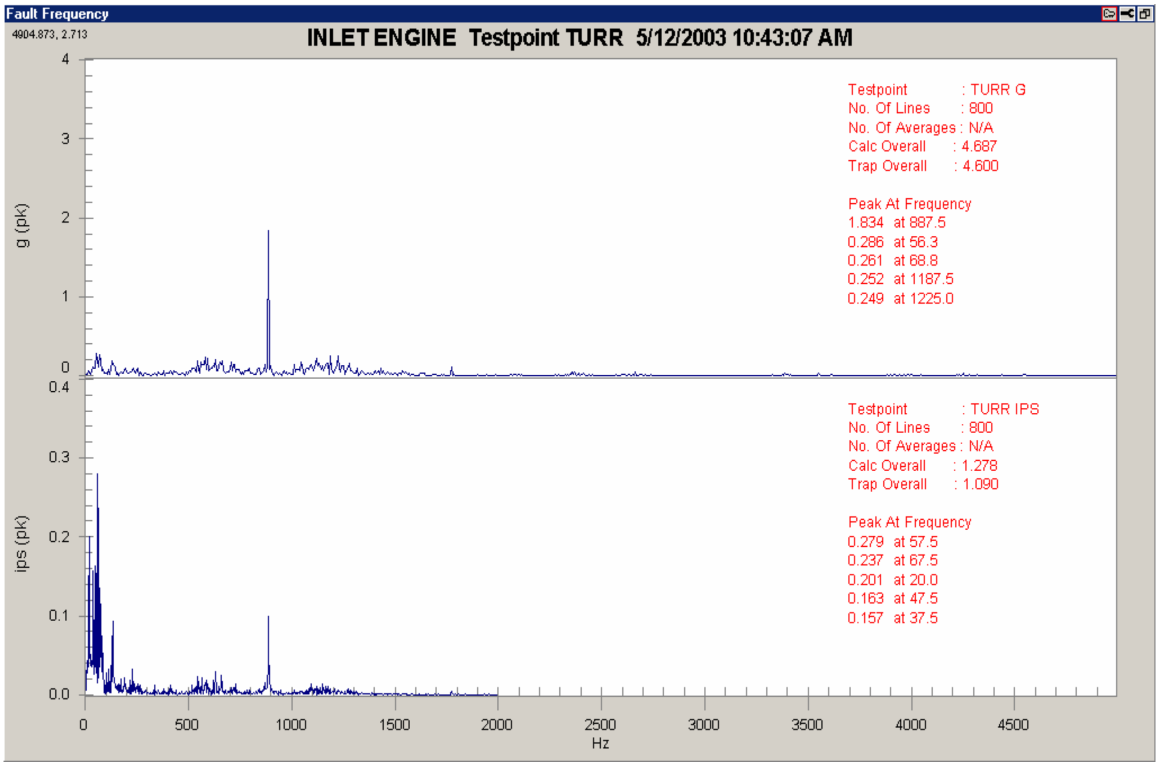
2.5 Act on the Findings of a Monitoring Plan

The last step in the development of a good monitoring plan is to act on the findings of the monitoring plan. This is not always easy, as it must be believed that the data is being interpreted correctly. The best way to believe the data trends is through experience, however, the gain of experience can be costly. This is illustrated in the following case study.

2.5.1 Case Study – Turbo Charger Vibration Data

The following data sets were collected from a Waukesha 9390 engine in western Alberta, over a six month period, during similar engine loading conditions. Figure 2 shows vibration data collected on the bearing between the compressor and turbine wheels of the engine right turbo charger in May 2003. At that time, the owner was notified of the high vibration levels at the first order of turbo run speed, and it was recommended that the impellers be inspected for damage or deposits, and the bearing for excessive wear.

No immediate action was taken. Figure 3 is a plot of vibration data at the same point, taken in July 2003, and similarly, Figure 4 data at the same point, taken in October 2003.



INLET ENGINE Testpoint TURR 5/12/2003 10:43:07 AM

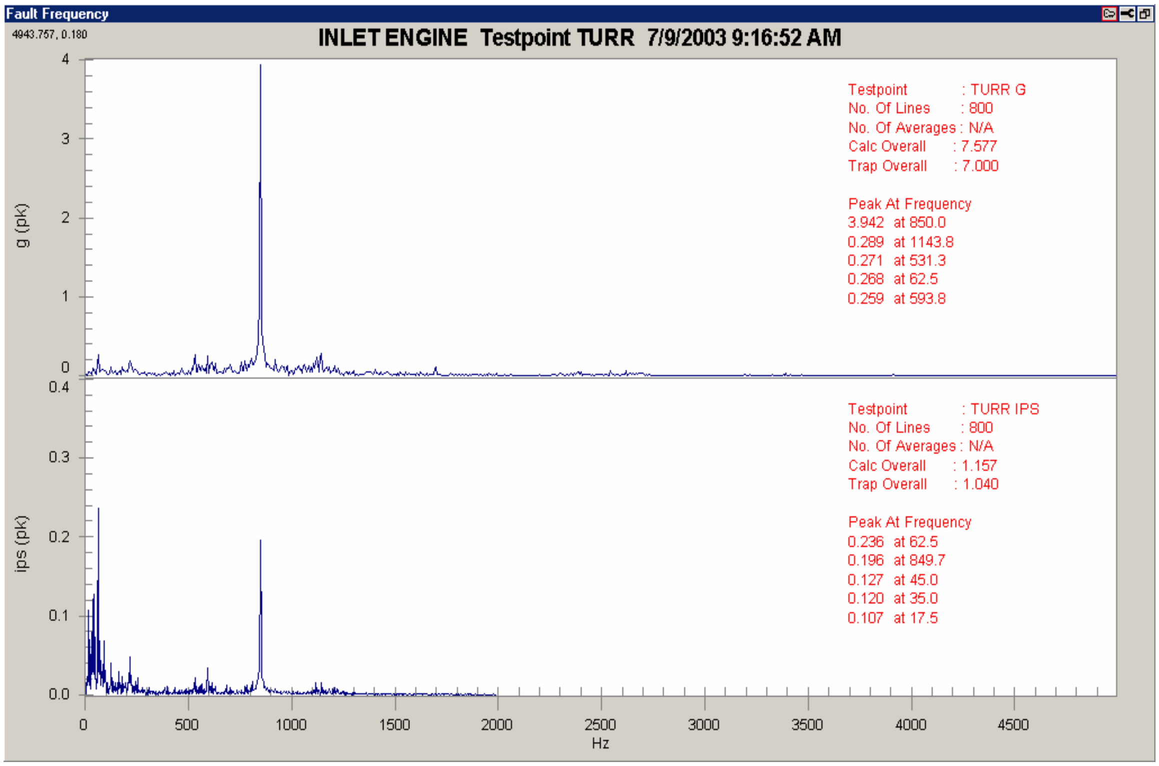
Testpoint : TURR G
No. Of Lines : 800
No. Of Averages : N/A
Calc Overall : 4.687
Trap Overall : 4.600

Peak At Frequency
1.834 at 887.5
0.286 at 56.3
0.261 at 68.8
0.252 at 1187.5
0.249 at 1225.0

Testpoint : TURR IPS
No. Of Lines : 800
No. Of Averages : N/A
Calc Overall : 1.278
Trap Overall : 1.090

Peak At Frequency
0.279 at 57.5
0.237 at 67.5
0.201 at 20.0
0.163 at 47.5
0.157 at 37.5

Figure 2 – Turbo Charger Vibration Data: First Data Set in May 2003



INLET ENGINE Testpoint TURR 7/9/2003 9:16:52 AM

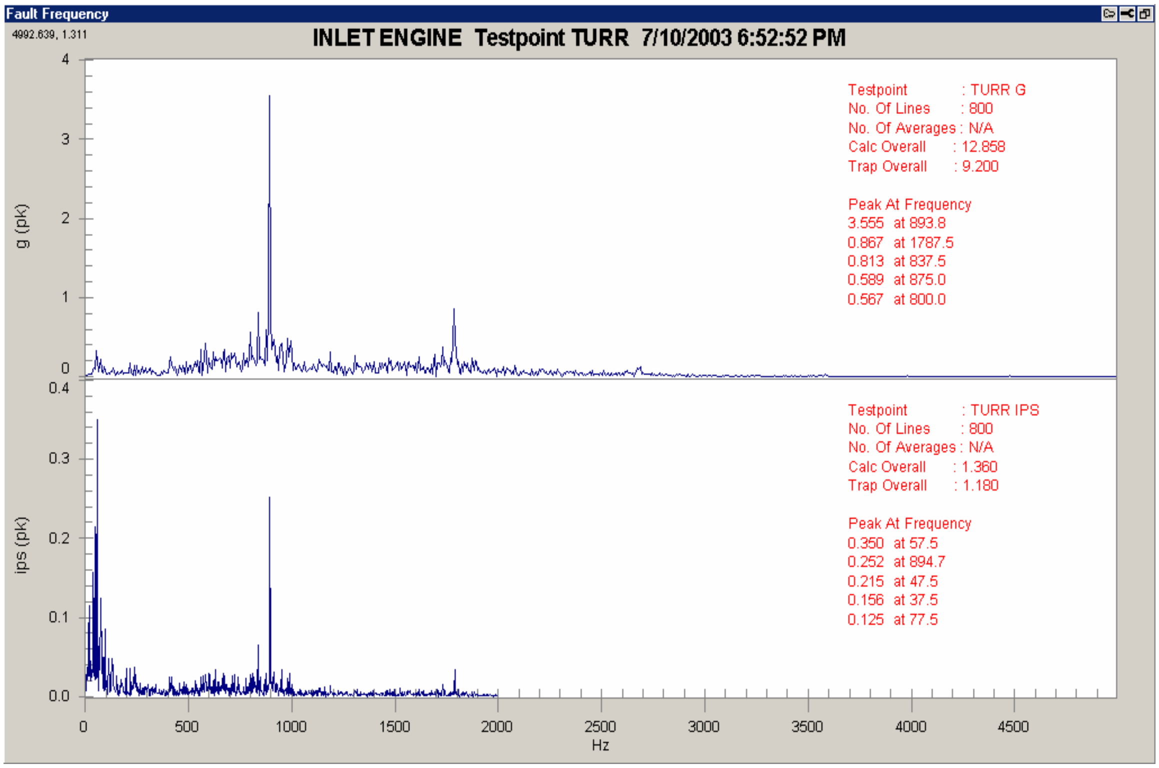
Testpoint : TURR G
No. Of Lines : 800
No. Of Averages : N/A
Calc Overall : 7.577
Trap Overall : 7.000

Peak At Frequency
3.942 at 850.0
0.289 at 1143.8
0.271 at 531.3
0.268 at 62.5
0.259 at 593.8

Testpoint : TURR IPS
No. Of Lines : 800
No. Of Averages : N/A
Calc Overall : 1.157
Trap Overall : 1.040

Peak At Frequency
0.236 at 62.5
0.196 at 849.7
0.127 at 45.0
0.120 at 35.0
0.107 at 17.5

Figure 3 – Turbo Charger Vibration Data: Second Set in July 2003



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Testpoint : TURR G
No. Of Lines : 800
No. Of Averages : N/A
Calc Overall : 12.858
Trap Overall : 9.200

Peak At Frequency
3.555 at 893.8
0.867 at 1787.5
0.813 at 837.5
0.589 at 875.0
0.567 at 800.0

Testpoint : TURR IPS
No. Of Lines : 800
No. Of Averages : N/A
Calc Overall : 1.360
Trap Overall : 1.180

Peak At Frequency
0.350 at 57.5
0.252 at 894.7
0.215 at 47.5
0.156 at 37.5
0.125 at 77.5

Figure 4 – Turbo Charger Vibration Data: Third Set in October 2003

In Figure 2, the first order of run speed for the turbo can be seen at about 850Hz. Note the increase in acceleration (g) and velocity (ips) levels at the first order between Figure 2 and Figure 3. Also note (in red type, top right corner of the figures) the increase in the overall vibration level between Figure 2 and Figure 3. The trend continues in Figure 4 with the overall value tripled when compared to that in Figure 2, while an increase in the second order is also visible at 1787Hz.

At the time of each data collection the owner was notified of the increasing vibration levels and inspection of the turbo was recommended. At no time were the recommendations acted upon. The results can be seen in Figures 5 and 6.

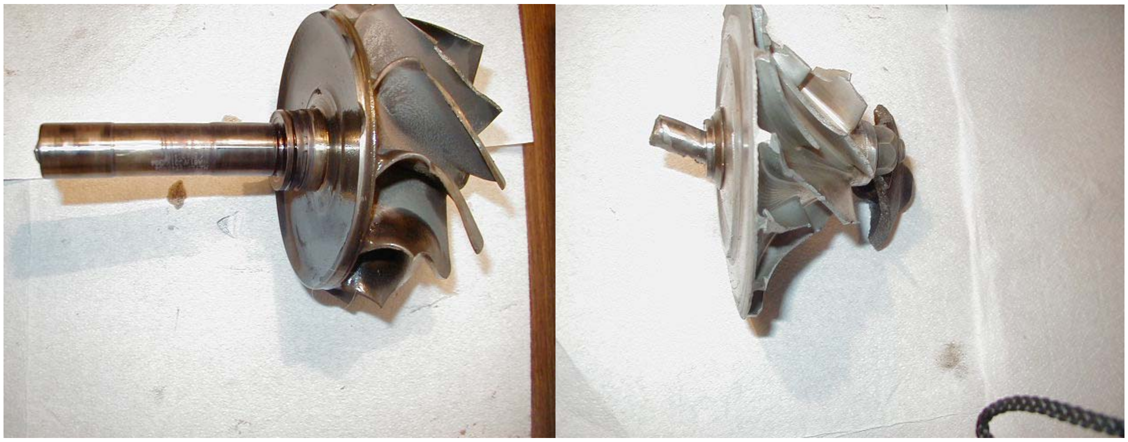

Figure 5 – Failed Turbo Charger Shaft and Impellers

Figure 6 – Failed Turbo Casing and Other Bits

The compressor wheel failed first, due to impeller rub against the casing. It is unknown how long the impeller was rubbing, sending wear particles into the aftercooler, intake manifold, and combustion chambers. The turbo charger was replaced with minimal attention paid to the cleaning of the engine components down the line.

Experience was gained in this case, but at the cost of $30,000-$40,000 turbo replacement, installation costs, and several days of down time. The consequences of the engine being run without a thorough cleaning of the components down the line from the turbo is unknown.

3. CONCLUSION

A condition monitoring plan is a worthwhile undertaking for a reciprocating engine. The four steps to develop a good condition monitoring plan are based on: the definition of an engine's failure modes, the identification of condition indicators for each failure mode, a plan to produce the condition indicators, and action on the findings from analysis of condition indicators. Lack of action can lead to costly gains in experience, as illustrated in the turbo charger vibration case study.

The application of a good condition monitoring plan for a reciprocating engine can yield such benefits as reduced maintenance, increased engine availability, and potential for process improvements leading to greater efficiency and profitability. These benefits are of interest to anyone operating a reciprocating engine, in any industry.

4. AUTHOR BIOGRAPHY

Jordan graduated from the University of Calgary with a Bachelor of Science in Mechanical Engineering in 2002. While on a trip around the world he got married, came home to Calgary, then joined Beta Machinery Analysis in 2003.

Jordan started off at Beta performing acoustical computer simulations of reciprocating compressor piping systems. These experiences led him to an interest in field troubleshooting and performance of reciprocating engines and compressors. Jordan is currently a Field Services Analyst for Beta Machinery Analysis.

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