

Analysis of High Speed Natural Gas Engine Valve Vibrations Using Statistical Methods

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Introduction

High-speed engines used in natural gas gathering applications have been shown to have a history of power valve failures.

This is especially true for exhaust valves, due to the high temperature environment to which the valve is exposed. In a paper presented at the GMRC 2007 Gas Machinery Conference[1], it has been shown that statistical techniques and histograms of valve vibration data can be used to identify valve faults that can lead to valve failures. This paper will discuss refinements made to the statistical techniques and calculations used to analyze valve vibration events. In addition, cause and effect data showing correlation between the statistical analysis and actual mechanical performance will also be presented.

This paper will present first-order differences between a nominally healthy valve and one that is potentially approaching failure. The differences are determined using statistical methods and verified by analysis of the actual mechanical components.

Background

Natural gas gathering applications typically use 4-stroke engines with either 2 or 4 valves per cylinder as the prime mover. **Figure 2.1** (below) depicts the basic cylinder head/valve layout. An accelerometer is typically used to gather vibration data from the valve events.

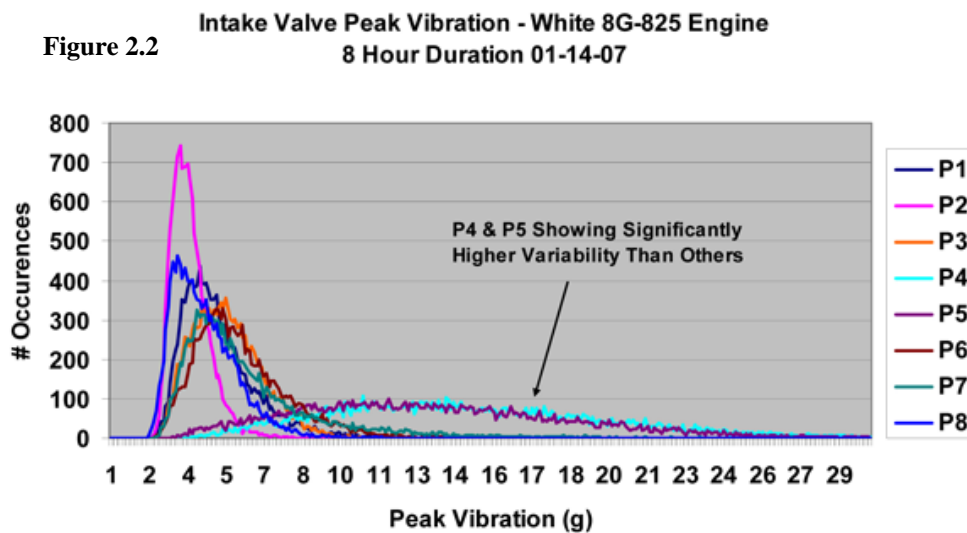


Figure 2.1

Field data gathered continuously over long time periods indicate that there can be significant variation in peak amplitudes as the valves close. This variation has also been observed in laboratory studies. The advent of relatively low cost and long term data acquisition hardware creates the opportunity to automate fault detection, especially for valve train problems.

Previous studies using a Data Acquisition System that gathered data over extended periods of time indicated that potential exists to automate fault detection process. The study conducted at that time indicated that the increase of variability of the vibration signature is potentially related to the fact that a component in the valve train was approaching failure.

The valve variability plot shown in **Figure 2.2** (below) shows a histogram of intake valve closing events for a White 8G-825 engine.



The data for this study was taken over an 8 hour period. The peak vibration for the valve closing events is plotted in a histogram format. The X-Axis (Peak Vibration) indicates peak vibration values in g's for a given closing event.

The Y-Axis (# Occurrences) indicates the number of times that a specific peak vibration value occurs over the 8 hour test period. Valves with a narrow pattern, such as P2, indicate that the peak closing valve vibration is more consistent over multiple cycles. Valves with wider patterns indicate that the closing vibration is less consistent over multiple cycles. It can be seen that intake valves for P4 & P5 have higher variability than the others.

This paper will present the results of using amplitude as an indicator of valve train condition as opposed to variability. The general method of data collection & fault detection will be discussed. Case studies will also be presented showing correlation of an automated fault detection algorithm with actual valve train condition.

Data Acquisition

Cylinder head accelerometer data is recorded for each degree of flywheel rotation over a long period of time. Events, such as intake valve closures (IVC), and exhaust valve closures (EVC), which occur during a specific window of the flywheel rotation, are detected. The peak vibration values of these events are determined, and written into a data storage element for each cylinder. The diagram in **Figure 3-1** shows the data acquisition and analysis system that was used.

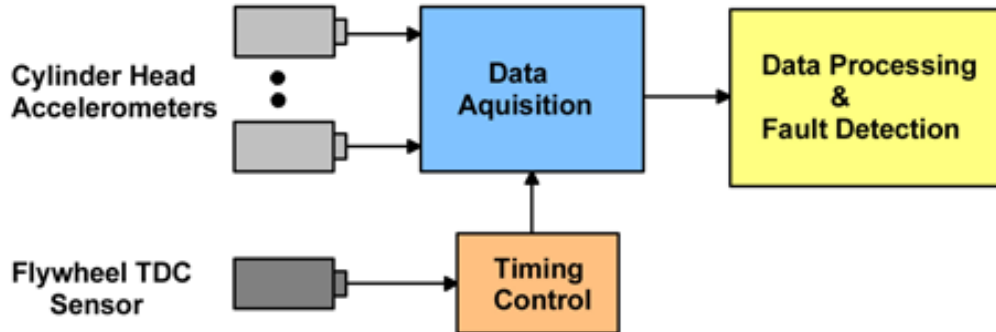


Figure 3-1 Data Acquisition / Analysis Block Diagram

Data Processing

The placement of the accelerometer sensor on a V12 configuration is typically done as shown in **Figure 4-1**. Note that a single accelerometer is used for 2 adjacent cylinders.

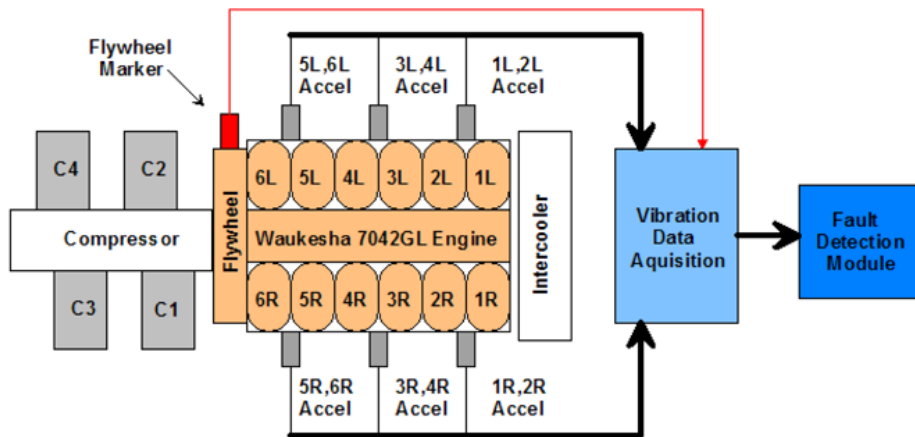


Figure 4-1 Accelerometer Placement on a V-12 Engine

After the data is collected, the Data Acquisition and Analysis System will apply statistical methods to establish a baseline of the engine under test. The baseline is used as a reference by the Fault Detection Module. This is where the core changes were made to the previously presented method of analysis. The previous method would generate histogram data that could be used to determine statistical variation of the vibrations for each valve. The refinements made to

the statistical calculations allow the system to generate detailed information about each type of event of interest, such as valve closures. **Figure 4-2** (below) shows typical data that would be collected on a V-12 four stroke engine, and the windows defined for IVC & EVC events within that vibration pattern.

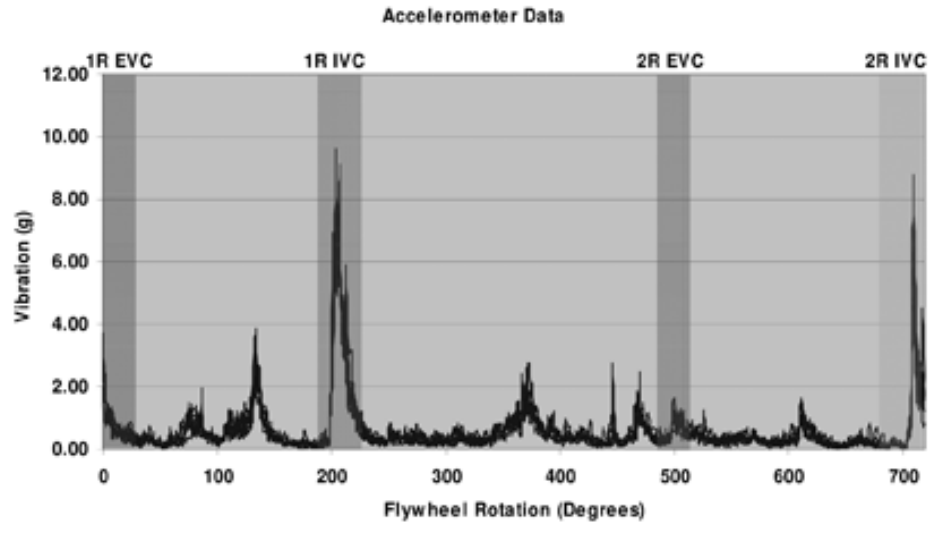
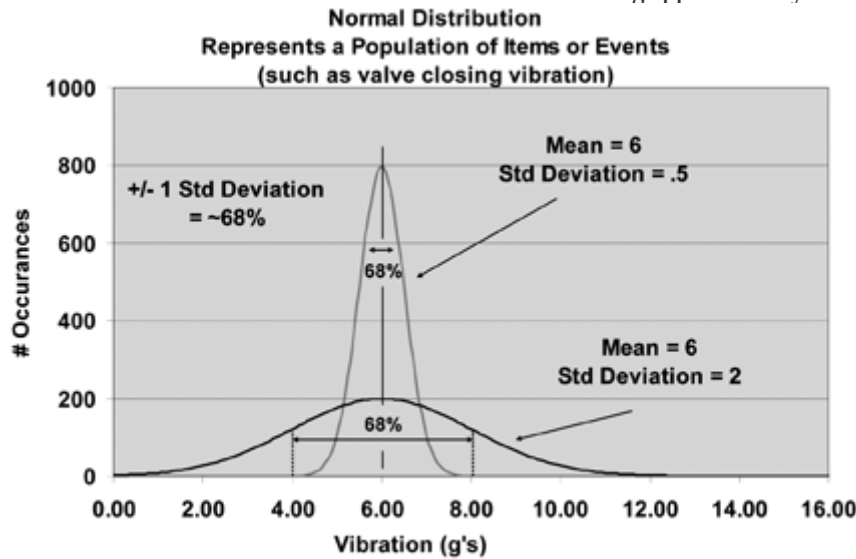


Figure 4-2 - Typical Vibration Data Captured on a V-12 Engine

Statistical Process

In previous studies of vibration data[1] it has been shown that the collected vibration data is bounded to a normal distribution of events. A normal distribution of data will have a bell shaped curve spanning approximately plus and minus one standard deviation from the mean and containing approximately 68% of the data.



An example of a normal

distribution is shown in Figure 5-1 (left). The chart shows the mean of the valve closing event is 6 g's. Two sets of data are drawn on the chart. The first set has a standard deviation of 0.5 g's and spans from 5.5 to 6.5 g's. A second curve

represents data with a much larger standard deviation of 2 g's. It also shows one standard deviation from the mean by spanning from 4 to 8 g's. Note that the second curve represents data with a significantly higher degree of variability.

Fault Detection

An assumption is made that mechanical events will follow a normal distribution. The Fault Detection Module will use the normally distributed base line data which contains a mean and standard deviation for each event and establish operating bands of normal (green / med. gray), warning (yellow / lt. gray) and alarm (red / gray) for an event. The bands are created by using configurable multipliers of the

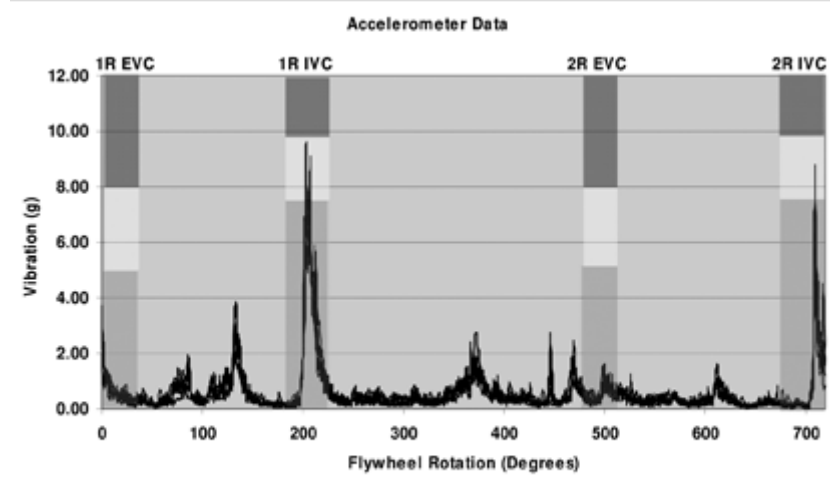


Figure 6-1 - Fault Detection Operating Bands

standard deviation from the mean. The

bands can be set individually for each event or applied to a group of like events. As can be seen in Figure 6-1 (right) which shows an example of operating bands, the intake & exhaust closing events have been grouped as like events. Note that different types of events can produce different normal, warning & alarm level bands. The Fault Detection Module will then use a patented algorithm to determine when an event crosses into a particular operating band.

Case Study - Waukesha 7042GL Engine

The Data Acquisition/Fault Detection System was mounted on a Waukesha 7042GL engine. This is a turbocharged, lean burn V-12 engine rated for 1488HP@1200 RPM. Accelerometers were mounted between cylinders using studs. Figure 7-1 (below) shows the engine used for testing. Figure 4-1 shows the accelerometer layout for this engine.

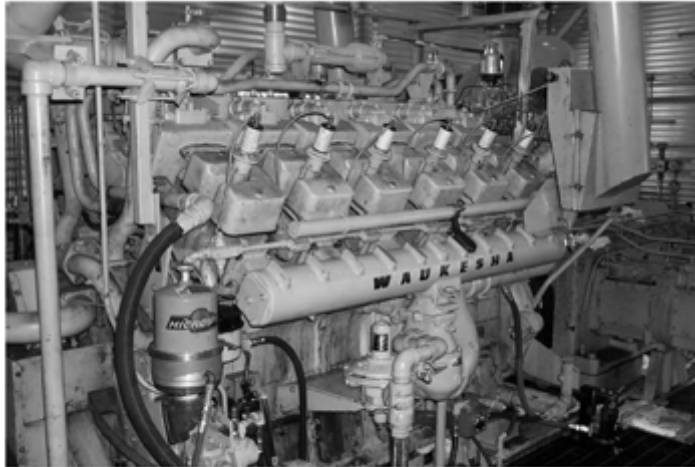


Figure 7-1 – Waukesha 7042GL Engine Used for Testing

Raw Vibration Data from the Data Acquisition System

Once the system was turned on, the alert limits for warnings & alarms were defined using the statistical technique & baseline generation described in a previous section. Decisions made by the Fault Detection Module are based on data gathered over extended periods of time. This insures that brief periods of high vibration are not reported as faults. The data gathered in Figure 7-2 & Figure 7-3 are snapshots of the data used by the Fault Detection Module. Average vibration levels are plotted for each cylinder head, as well as the normal (green), warning (yellow) and alarm (red) levels determined by the system.

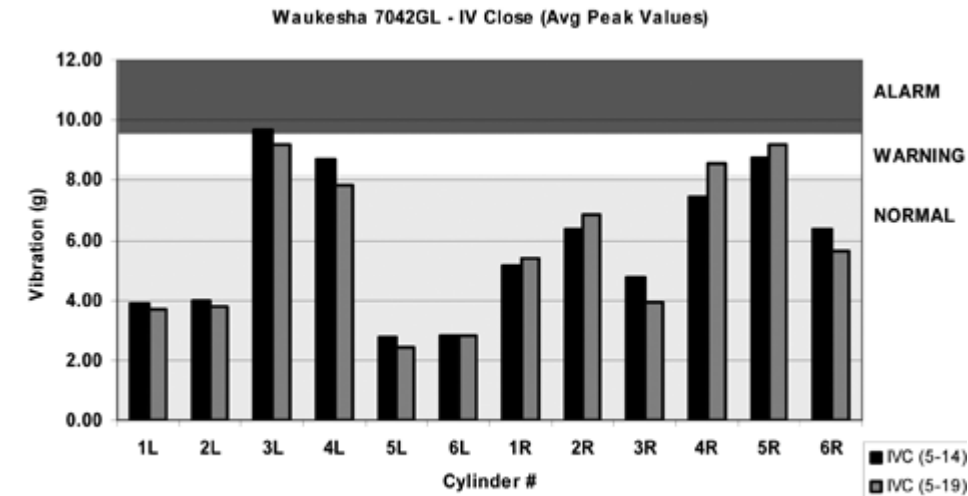


Figure 7-2 & Figure 7-3 show data recorded at different dates. This was done to determine that the results were consistent over extended periods of time.

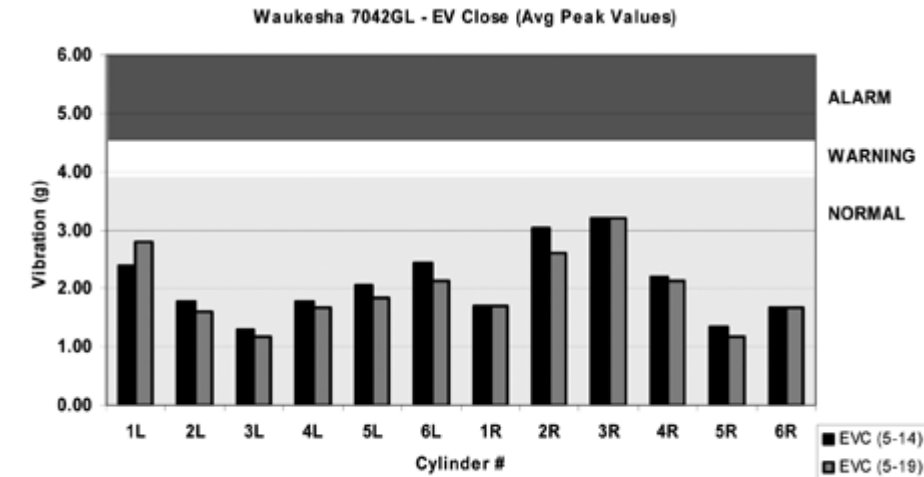


Figure 7-3 - Exhaust Valve (EV) Closure - Summary of Vibration Levels

Anomalies Reported by the Fault Detection Module

It can be seen from the data that intake valves 3L, 4L, 4R, & 5R have been identified by the Fault Detection Module as having higher vibration levels compared to the other valves in the engine. It can also be seen, that, 4L & 4R were, at different dates, not identified as problems by the Fault Detection Module. This phenomenon has been seen on other occasions where a failing component, early in the progression of that failure, will sometimes exceed the alert threshold, and sometimes it will be just below this threshold.

In addition to the faults seen in the data in Figure 7-2 & Figure 7-3, additional faults were reported on exhaust valves 1L & 3L. These were not seen in the data snapshots due to the fact that their behavior was not exceeding an alert threshold when the data was taken.

Table 1 (below) shows the complete list of valve vibration alerts reported by the Fault Detection Module.

Event	Comment
3L IV Close	Warning (yellow) to alarm (red) reported
4L IV Close	Normal (green) to warning (yellow) reported
4R IV Close	Normal (green) to warning (yellow) reported
5R IV Close	Warning (yellow) reported
1L EV Close	Alerts reported previous to dates snapshot data was gathered
3L EV Close	Alerts reported previous to dates snapshot data was gathered

Table 1 – Valve Events Reported by the Fault Detection Module

Data Gathered from a Portable Analyzer

In order to prove that the Fault Detection Module was correctly reporting valve problems, a portable analyzer was used to take data on the engine. Figure 7-4 & Figure 7-5 (below) show the portable analyzer vibration traces used to determine how well they correlate with results from the Fault Detection System.

The Data Acquisition/Fault Detection System and a portable analyzer will have a slightly different view of the valve events due to the fact that one is continuously monitoring, and the other is only attached when data is taken. Also, the Fault Detection Module uses an algorithm that determines if event amplitude exceeds a specific threshold. As such, the Fault Detection Module will not report issues where windows are not specified.

The portable analyzer vibration data for the left bank (Figure 7-4) show cylinders 3L & 4L have higher vibration values for the intake closing events. The Data Acquisition/Fault Detection system reported these same intake valves as having higher vibration values.

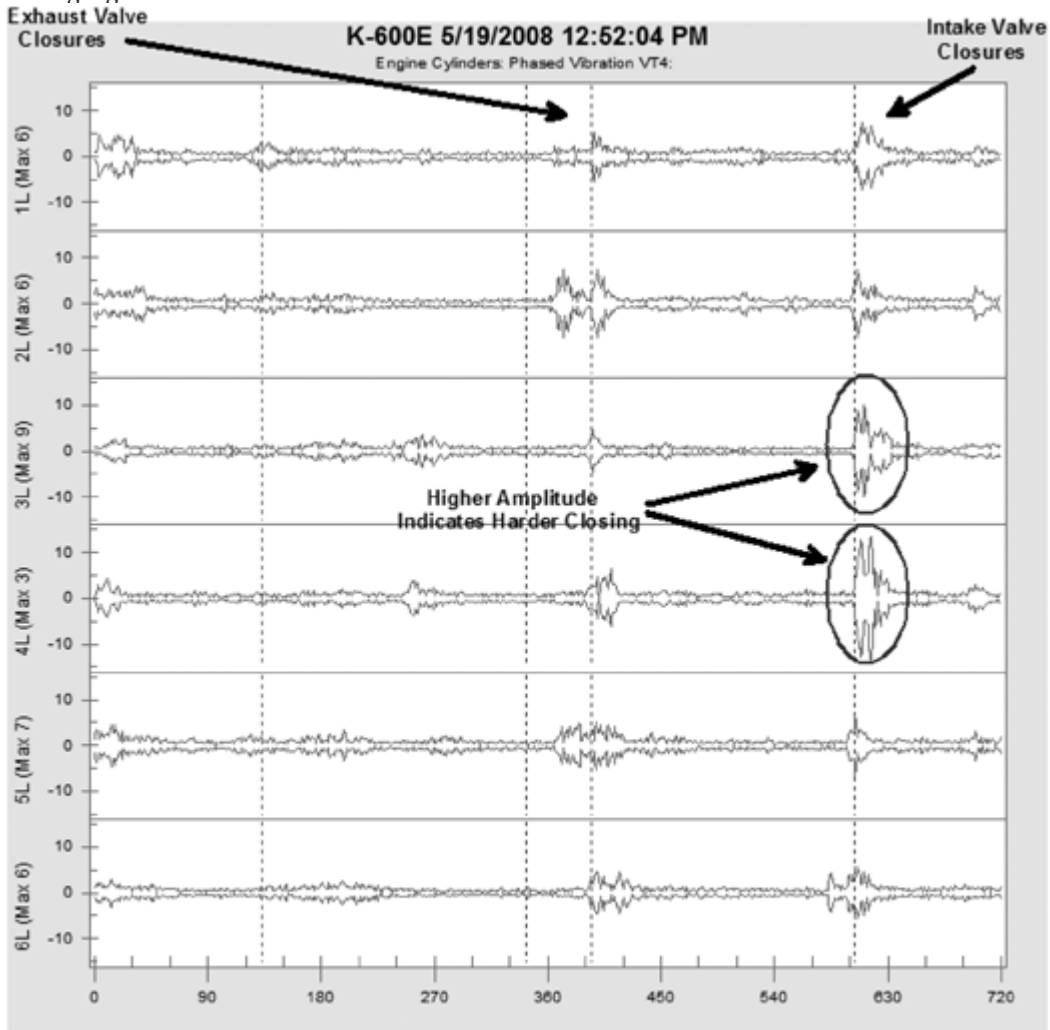


Figure 7-4 – Left Bank Vibration Data from Portable Analyzer (Max Values)

Exhaust valve event data from the portable analyzer show that no valves are closing harder than expected. The Data Acquisition/Fault Detection System indicated exhaust valves 1L & 3L as having harder closing events on an earlier date, then after a period, reported their behavior as normal. Subsequent inspection of the valve train for EV 1L & 3L indicated that the lifters appeared to collapse then recover for a period of time.

The portable analyzer vibration patterns for the right bank (Figure 7-5) show cylinders 1R, 2R, 3R, 4R, 5R, & 6R have high vibration values for the intake closing events. The Data Acquisition/Fault Detection system reported 4R & 5R as having high vibration values. This appears to be a discrepancy unless the minimum & maximum values for the portable analyzer are taken into account.

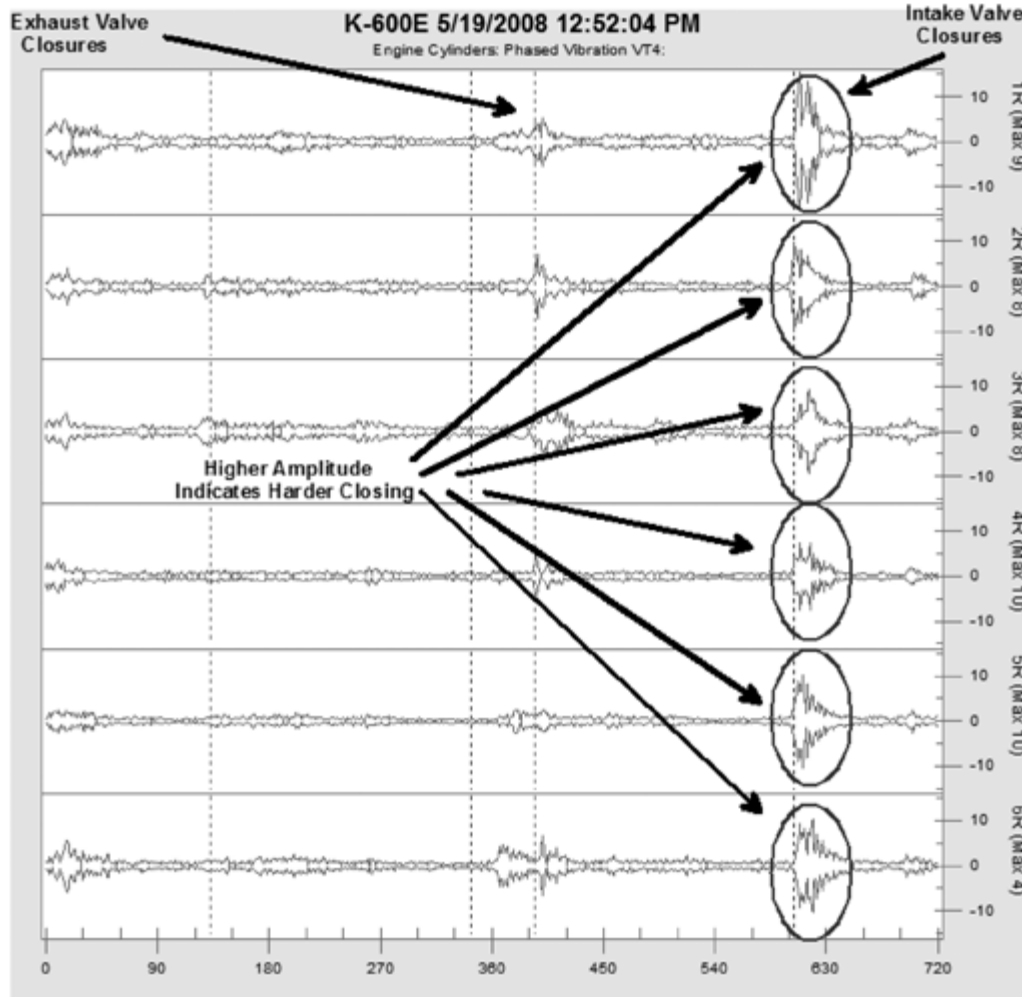


Figure 7-5 - Right Bank Vibration Data from Portable Analyzer (Max Values)

Prior to gathering data using a portable analyzer, a valve adjustment was performed. It was subsequently determined that the right side valves were improperly adjusted, which would account for the consistently high vibration on the right side.

Studying the minimum & maximum vibration levels recorded by the portable analyzer, it can be seen that there is variation in the min & max values. The Data Acquisition/Fault Detection System algorithms are specifically designed to filter these variations. Only sustained events that exceed a threshold are reported as problems.

It is also important to note that the portable analyzer data is only a result of 10 cycles, while the Data Acquisition/Fault Detection System processes data continuously, and the reported alerts are based on thousands of cycles. As such, the data from the portable analyzer should be used a guide when attempting to correlate reported alerts from the Data Acquisition/Fault Detection System. Exact correlation cannot be expected.

Valve Train Component Analysis

Shortly after the data was taken, the engine & cylinder heads were disassembled for maintenance and analysis. Table 2 shows the results of analysis of the valve train condition, and how well it correlates to what the Fault Detection System reported.

Item 3 in Table 2 (3L IV Close): Good correlation was seen between the Fault Detection System, portable analyzer, and an actual inspection of the valve train. During the inspection, a weak valve lifter was discovered on this valve.

Item 4 in Table 2 (4L IV Close): Good correlation was seen between the Fault Detection System, portable analyzer, and an actual inspection of the valve train. During the inspection, a weak valve lifter was discovered on this valve.

Item 10 in Table 2 (4R IV Close): Good correlation was seen between the Fault Detection System, portable analyzer, and an actual inspection of the valve train. During the inspection, a weak valve lifter was discovered on this valve. It is important to note that the valves were improperly adjusted on the right side of the engine just before the portable analyzer data was gathered.

Item 11 in Table 2 (5R IV Close): Good correlation was seen between the Fault Detection System, portable analyzer, and an actual inspection of the valve train. During the inspection, a weak valve lifter was discovered on this valve. It is important to note that the valves were improperly adjusted on the right side of the engine just before the portable analyzer data was gathered.

Item 13 in Table 2 (1L EV Close) is reported as a problem by the Fault Detection System, however, it cannot be seen using a portable analyzer. Fault logs show that the problem was intermittent between 5-3-08 & 5-6-08, then went away. During the inspection, a weak valve lifter was discovered on this valve.

Item 15 in Table 2 (3L EV Close) showed no problem reported by the Fault Detection System, nor the portable analyzer. An inspection showed that the rocker arm bushing was .180" over tolerance.

Item 21 in Table 2 (3R EV Close) was reported as a problem by the Fault Detection System. An inspection revealed a weak lifter. The fault logs show that the problem was intermittent between 4-7-08 & 4-9-08, then after a period of time, went away.

Item	Event	Fault Detection Alert?	Portable Analyzer	Inspection Results	Notes
1	1L IV Close	No	Normal Vibration Amplitude		
2	2L IV Close	No	Normal Amplitude		
3	3L IV Close	Yes	High Amplitude	Weak Lifter	
4	4L IV Close	Yes	High Amplitude	Weak Lifter	
5	5L IV Close	No	Normal Amplitude		
6	6L IV Close	No	Normal Amplitude		
7	1R IV Close	No	High Amplitude, High Variability		Improper valve adjustment on right side
8	2R IV Close	No	High Amplitude; High Variability		Improper valve adjustment on right side
9	3R IV Close	No	Normal Amplitude		Improper valve adjustment on right side
10	4R IV Close	Yes	High Amplitude, High Variability	Weak Lifter	Improper valve adjustment on right side
11	5R IV Close	Yes	High Amplitude, High Variability	Weak Lifter	Improper valve adjustment on right side
12	6R IV Close	No	High Amplitude		Improper valve adjustment on right side
13	1L EV Close	Yes	Normal Vibration Amplitude	Weak Lifter	Collapsing then recovering lifter. Log only showed fault on 5-3-08 to 5-6-08.
14	2L EV Close	No	Normal Vibration Amplitude		
15	3L EV Close	No	Normal Vibration Amplitude		Rocker arm .18 over tolerance
16	4L EV Close	No	Normal Vibration Amplitude		
17	5L EV Close	No	Normal Vibration Amplitude		
18	6L EV Close	No	Normal Vibration Amplitude		
19	1R EV Close	No	Normal Vibration Amplitude		Improper valve adjustment on right side
20	2R EV Close	No	Normal Vibration Amplitude		Improper valve adjustment on right side
21	3R EV Close	Yes	Normal Vibration Amplitude	Weak Lifter	Collapsing then recovering lifter. Log only showed fault on 4-7-08 to 4-9-08 Improper valve adjustment on right side
22	4R EV Close	No	Normal Vibration Amplitude		Improper valve adjustment on right side
23	5R EV Close	No			Improper valve adjustment on right side
24	6R EV Close	No			Improper valve adjustment on right side

Table 2 - Analysis of Actual Mechanical Valve Train Condition

Summary

Good correlation between the Fault Detection System, portable analyzer, and a physical inspection was seen on this engine. Due to the fact that the valves on the right side were misadjusted, the portable analyzer showed high vibration levels on all the intake valve closing events. In some cases, the Fault Detection System did not see this increase as sufficient to cross an alert threshold. In cases where the Fault Detection System did cross an alert threshold, an actual anomaly was seen during the physical inspection.

Case Study – Caterpillar 3608 Engine



Figure 8-1 - Caterpillar 3608 Engine Under Test

The Data Acquisition/Fault Detection System was mounted on a Caterpillar 3608 engine. This is a turbocharged inline-8 cylinder engine. Accelerometers were mounted between cylinders using studs. Figure 8-1 (above) shows the engine used for testing. Figure 8-2 (below) shows the accelerometer layout for this engine.

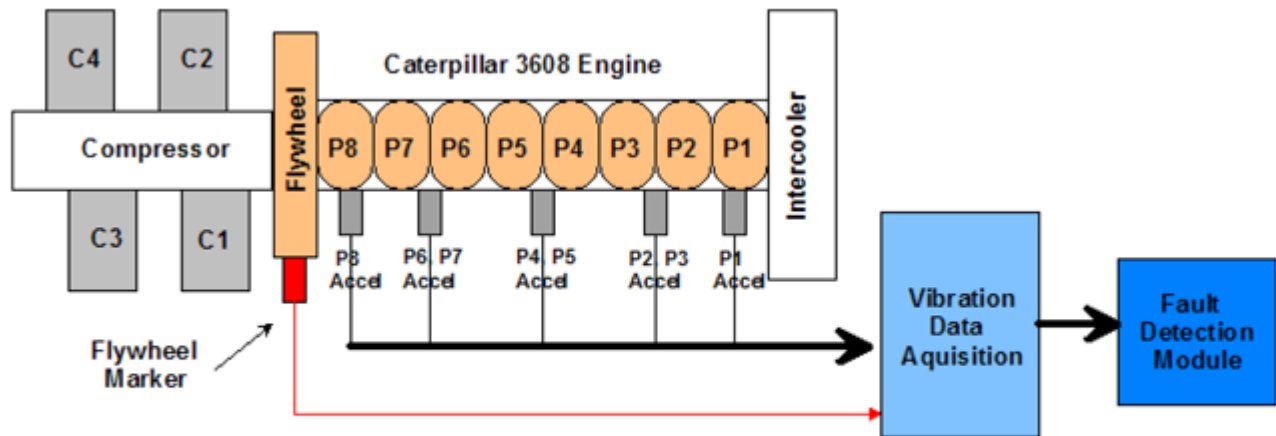


Figure 8-2 - Accelerometer Layout for the Caterpillar 3608 Engine

Raw Vibration Data from the Data Acquisition System

Once the system was turned on, the alert limits for warnings & alarms were determined using the statistical technique & baseline generation described in the Statistical Process section.

The data gathered in Figure 8-3 & Figure 8-4 are snapshots of the data used by the Fault Detection Module. Average vibration levels are plotted for each cylinder head, as well as the warning and alarm levels determined by the system.

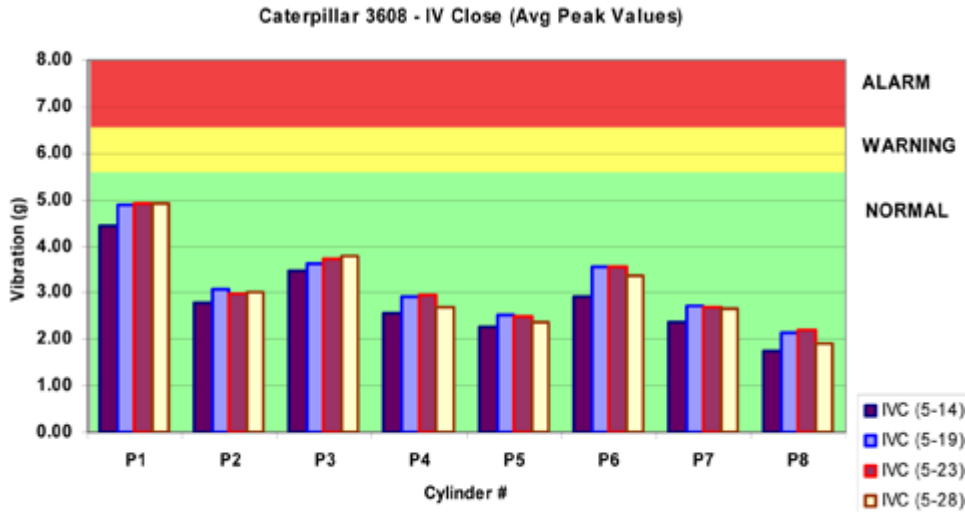


Figure 8-3 - Intake Valve (IV) Closure - Summary of Vibration Levels
Caterpillar 3608 - EV Close (Avg Peak Values)

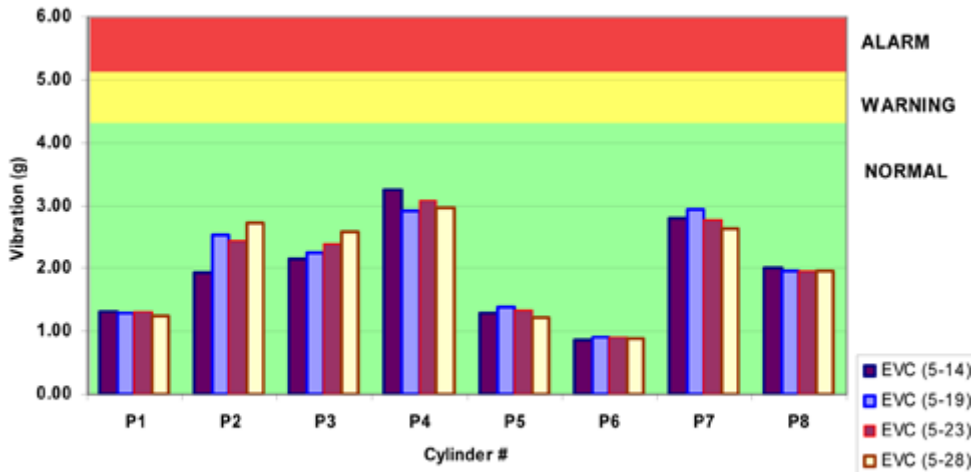


Figure 8-4 - Exhaust Valve (EV) Closure - Summary of Vibration Levels

Amplitudes for each cylinder are shown, along with the alarm bands normal (green), warning (yellow) and alarm (red).

Anomalies Reported by the Fault Detection Module

In this case, snapshots of the vibration levels taken on 4 different dates show that none of the vibration amplitudes exceed the normal level. Also, the data shows a high degree of consistency for all 4 snapshots. No alerts were reported by the Fault Detection Module, which supports the snapshot data shown in Figure 8-3 & Figure 8-4.

Data Gathered from a Portable Analyzer

As before, a portable analyzer was used to determine if the vibration patterns from the analyzer are consistent with the fact that the Fault Detection Module is not reporting problems with the valve closing events. Figure 8-5 & Figure

8-6 show the portable analyzer vibration patterns.

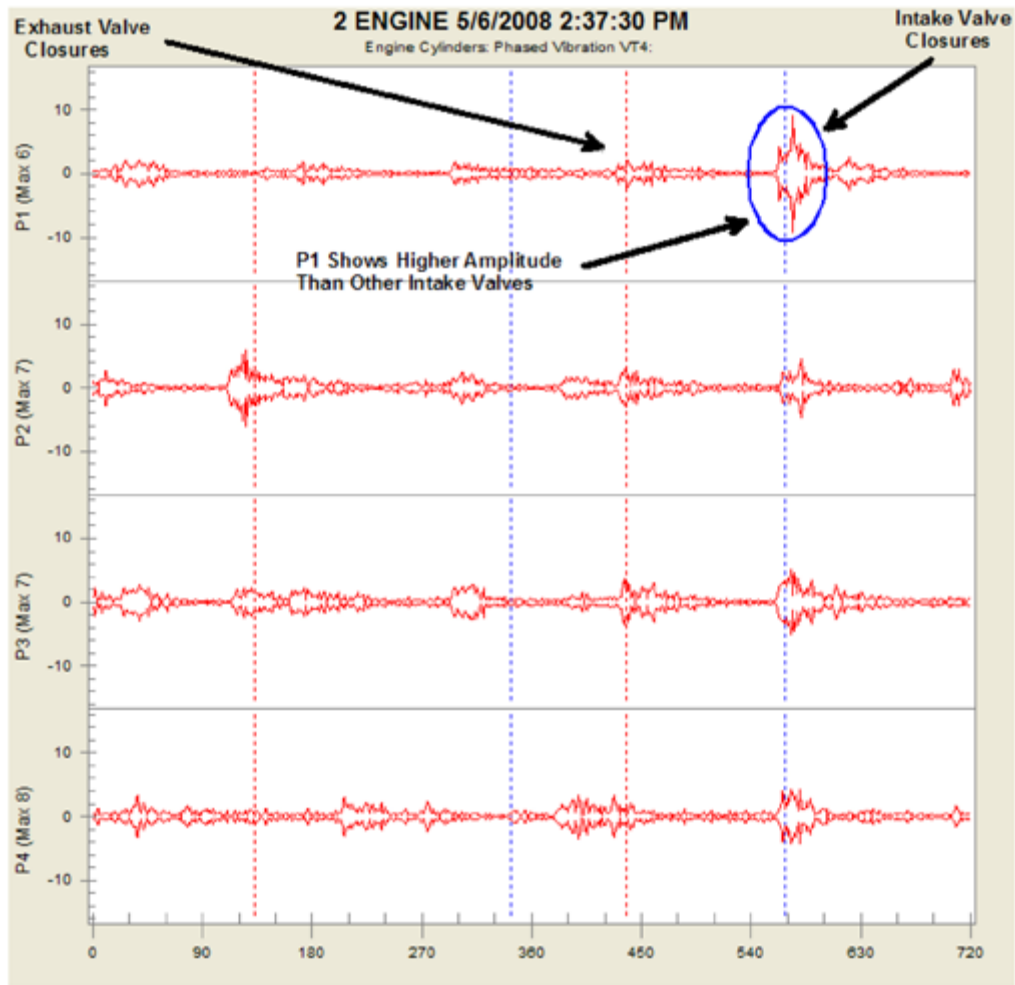


Figure 8-5 – P1 – P4 Vibration Data from Portable Analyzer (Max Values)

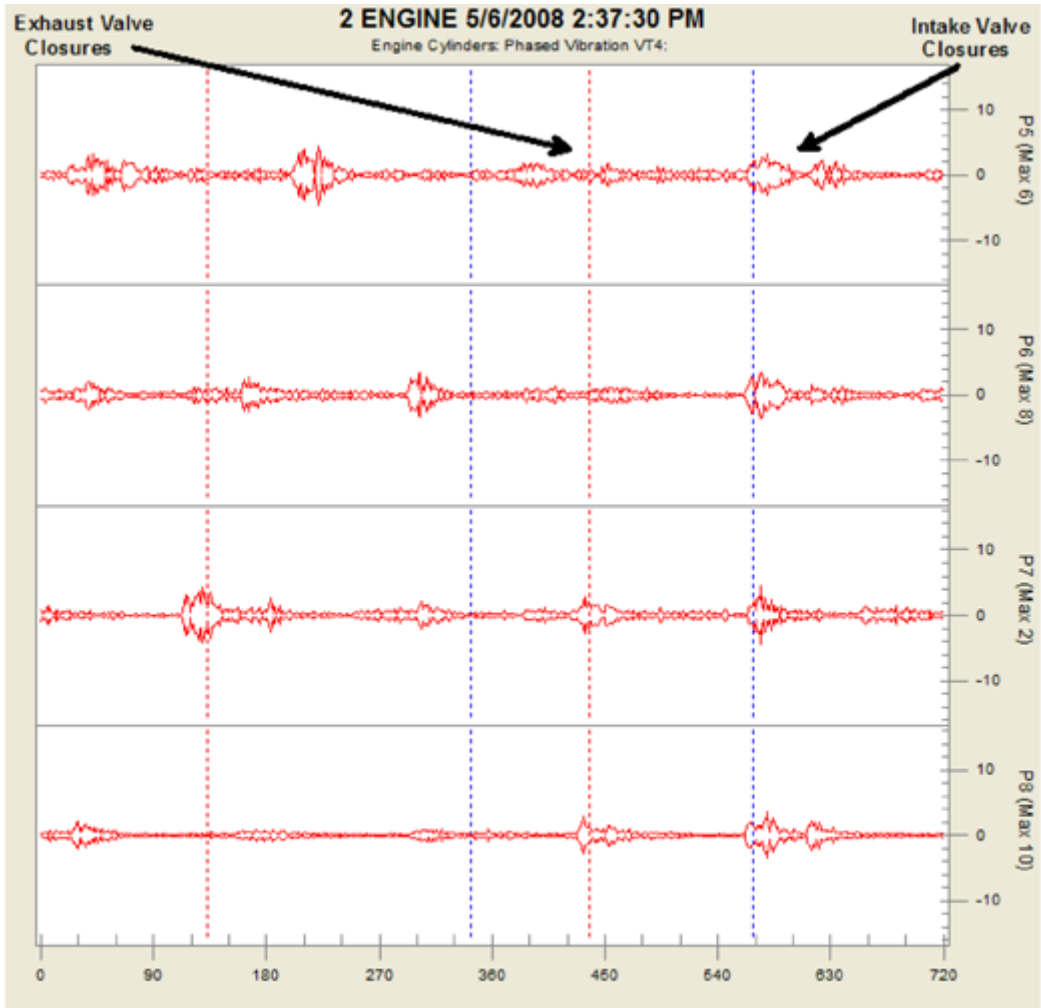


Figure 8-6 - P5 – P8 Vibration Data from Portable Analyzer (Max Values)

These patterns show a higher peak vibration for P1 Intake Close. This higher vibration can also be seen in the data taken by the Data Acquisition System. However, in the case of the Fault Detection System, the warning & alarm thresholds were set to a value that sustained vibration events caused by this valve closure did not exceed.

Valve Train Component Analysis

Shortly after the data was taken, the engine was disassembled, and the cylinder



Figure 8-7 – Cylinder Head for Caterpillar 3608 Engine

heads removed for scheduled maintenance. In this case, inspection of the valve train components revealed no issues that would lead to imminent failure. This is consistent with the fact that the Data Acquisition/Fault Detection System reported no problems, and the data taken with a portable analyzer also showed no problems. Figure 8-7 shows the combustion chamber for cylinder head P3.

Summary

Upon inspection, the valve train in this engine was determined to be in good condition. This fact can be correlated by the both the Fault Detection System and the results from a portable analyzer. In the case of P1 IVC, both the Fault Detection System and the portable analyzer registered higher levels of vibration levels. These high vibration levels did not increase sufficiently to cross a warning or alarm threshold.

Conclusions

Automated analysis of valve vibration using algorithms based on statistical method show good correlation with both data taken from a portable analyzer, and actual inspection of the valve train.

Case studies show that intermittent conditions will cause discrepancies between systems that monitor vibration continuously and those that take snapshots of data at periodic intervals. This is to be expected. If the anomaly becomes more consistent, the Fault Detection System will then raise an alert.

The use of vibration amplitude & statistical analysis, as opposed to vibration variability, has shown to be an effective technique for identifying valve train problems before they progress to the stage of catastrophic failure. This presents significant opportunity for savings, as well as lower maintenance costs, & reduced downtime.