Case Study:
How Recurring Oil Pan Cracks on Large High Speed Gas Engines were Investigated and Resolved

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Abstract

The following case study illustrates issues with oil pans developing cracks shortly after being put into service on large, high-speed gas engines. Cracks developed on the bottom of several Williams' engine oil pans in late October 2014 after accumulating no more than 70 hours of run time. This prompted Williams, Caterpillar, and 6D Testing & Analysis to identify suspect oil pans and initiate an investigation. The process taken to identify the cause of the oil pan cracks including the details of the investigation, analyses, and test results are described in the following paper.

The removal and inspection of the oil pans, crack inspection, and examination of the history and previously completed vibration studies are covered in the investigation. The analysis details the finite element analysis performed by 6DOF used to create a test plan to measure high dynamic stresses, natural frequencies, and mode shapes. Finally, the impact test results, dynamic strain measurements, and operating deflection shape data taken on one of the oil pans are reviewed.

The goal of this case study is to highlight the engineering involved with investigating high cycle fatigue cracks due to resonance.

Introduction

Any failure represents a substantial amount of downtime, loss of production, and personnel resources. Specifically, unexpected failures with reciprocating compressors and engines require a methodical troubleshooting approach in order to determine the root cause. Therefore, it is imperative that the engineers involved evaluate all potential scenarios and substantiate recommended solutions with facts. A non-typical failure, such as the one described in this case study, can be particularly difficult to troubleshoot and will require more time and resources to come to a solution. However, the amount of down time and risk can be significantly reduced when done properly through thoughtful testing and analysis. This case study presents the facts and troubleshooting methods used to investigate cracks on several large high speed gas engines.

Background and History

The oil pans on the bottom of several Caterpillar (CAT) 3612 engines, as seen in Figure 1, developed cracks in late 2014.

Figure 1: CAT 3612 Engine

All of the cracks occurred on newly commissioned units and were on the bottom of the oil pan. Williams, CAT, and their testing contractor 6DOF took a methodical troubleshooting approach in evaluating the cause.

The first oil pan crack, shown in Figure 2**,** occurred in late 2014 after only 66 hours of operation. As shown in Figure 3Error! Reference source not found.**,** the crack occurred on the bottom of the pan. Therefore, it was necessary for CAT and Williams to immediately remove the oil pan from the engine to be shipped to CAT for non-destructive testing (NDT) to assess the cause of the unexpected failure.

Figure 2: Crack on the Bottom of the Oil Pan

Figure 3: Location of the Crack

The process of removing an oil pan from a large high-speed engine is not a typical procedure and requires special precaution and cribbing in order to maintain the integrity of the pan for later examination. Photos of the procedure are shown in Figure 4 and Figure 5**.**

Figure 4: Roller Track used to Remove Oil Pan from Engine

Figure 5: Oil Pan being removed from the Engine via Roller Tracks

While CAT performed NDT on the failed oil pan, Williams inspected other identical packages and performed a review of the design looking for other clues to the cause of the failure.

Failure Investigation and "History"

After being informed of the potential issue with oil pans cracking in the field, Tier II product support engineers from CAT gathered all pertinent information including customer (Williams) inquiry via the Dealer Service Network, engine serial number, engine hours, application, etc. This information is used by CAT to help troubleshoot the failure and recommend an interim corrective action. A CAT tech dispatched to the site found a crack on the left of the oil pan about a third of the way back. It appeared to be located on the weld between the bottom and side plates of the pan. No other visual damage to the bottom of the pan was found.

The CAT Tier II team reviewed the commissioning report and requested the failed components be sent back to the factory for testing and failure analysis. The team's goal was to determine the failure mode of the component and develop a plan to uncover the root cause using the six sigma DMAIC process.

Through their investigation, CAT found only two other pan failures throughout the history of the G3612 in the compression application. While the failure rate was extremely low, the high cost of replacing a failed pan prompted the launch of an internal continuous product improvement issue. The investigation at CAT internally along with the support from Williams and 6DOF is further discussed below.

Post Commissioning Vibration Survey

A portion of the history that was available was a post commissioning vibration survey, which was performed on all of the CAT 3612 units at the station. A typical vibration survey consists of measuring locations on the compressor, engine, skid, and piping. The survey looks for global issues and would not necessarily focus on a localized issue. Additionally, since the oil pan is difficult to get to it would be unusual for vibration measurements to be taken near the location where the crack occurred.

As expected, the vibration survey identified high vibration on parts of the compressor and piping, but no measurements were taken near the crack. Speed limits were put in place to protect the vibrating components. This is a typical approach until remediation efforts can be put in place to correct the vibration levels. Unit 1 could only be operated at 920 RPM, Unit 2 from 945 to 950 RPM, and Unit 3 from 940 to 960 RPM. In this situation, the speed limits placed the unit in a non-typical operating speed that accelerated the cracks.

Non-destructive Testing

Inspection of the oil pan found a crack along the bottom plate of the oil pan, adjacent to the weld. The pan was sectioned and the crack was opened up to examine the fracture in detail.

An overview of the oil pan, with the location of the crack marked is shown in Figure 2 and Figure 3. A closer view of the crack is shown in Figure 6.

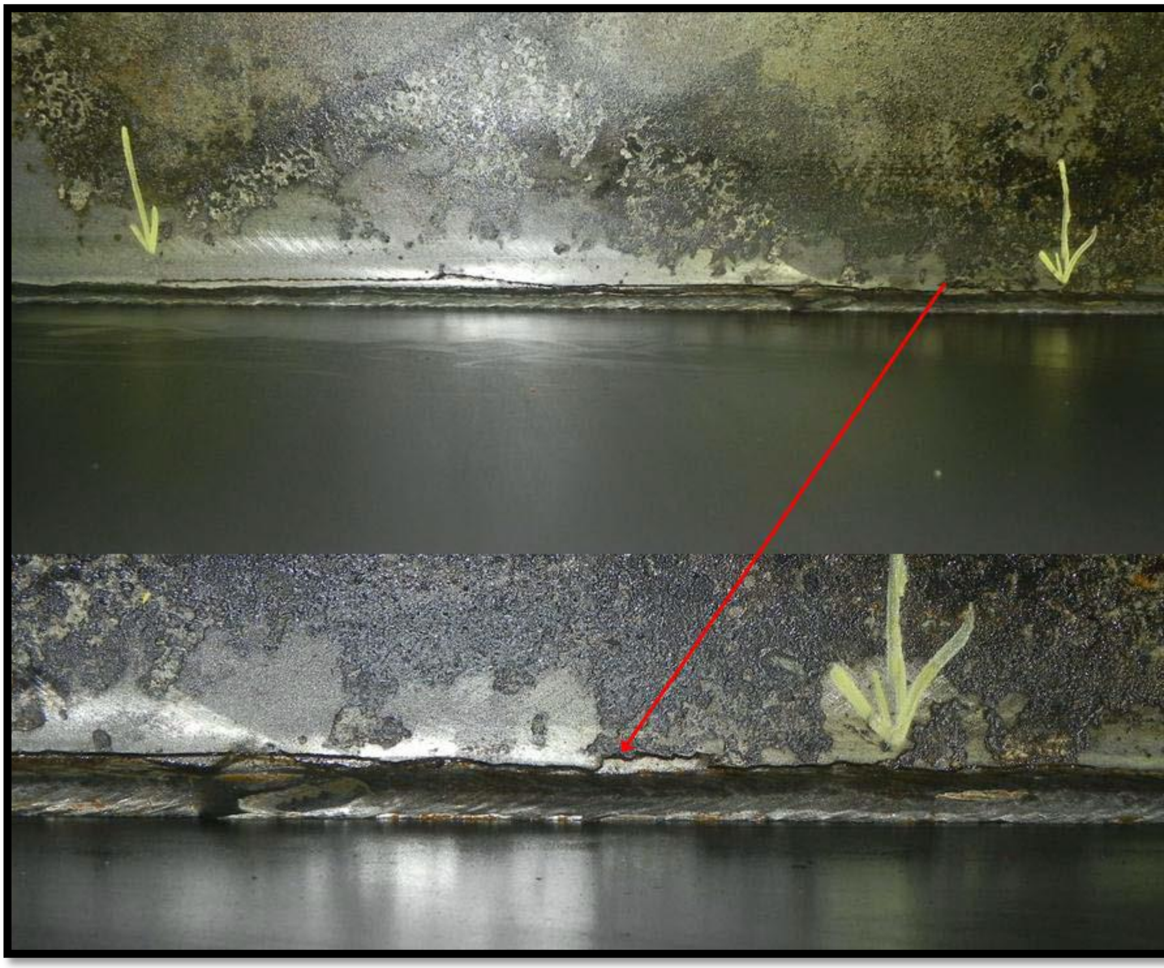

Figure 6: Closer View of Crack

The pan was sectioned and the crack was opened up to examine the fracture surface, Figure 7.

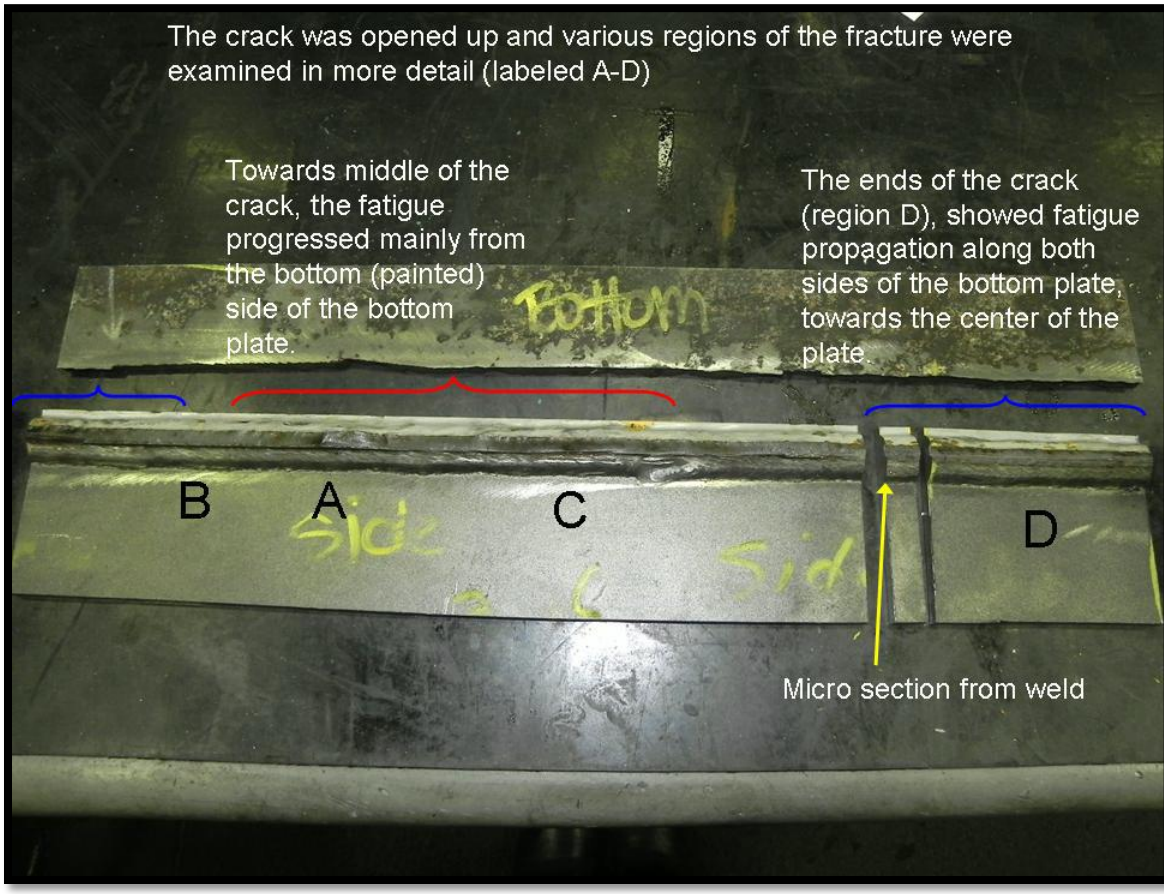

Figure 7: Oil Pan Sectioned for Examination

Towards the middle of the crack, fatigue from multiple origins propagated primarily from the bottom (painted) side of the bottom plate, Figure 8: Microscopic View of Fatigue Propagation. The ends of the crack showed fatigue propagation along both sides of the bottom plate, towards the center of the plate thickness. Microscope inspection of the weld near the crack and away from the crack showed good fusion, acceptable fillet leg and throat size, and no defects. Fatigue propagated from multiple origins along both sides of the bottom plate, towards the center of the plate. Fatigue progressed primarily from the bottom (painted side) of the bottom plate. This could indicate higher stress along the bottom side of the bottom plate.

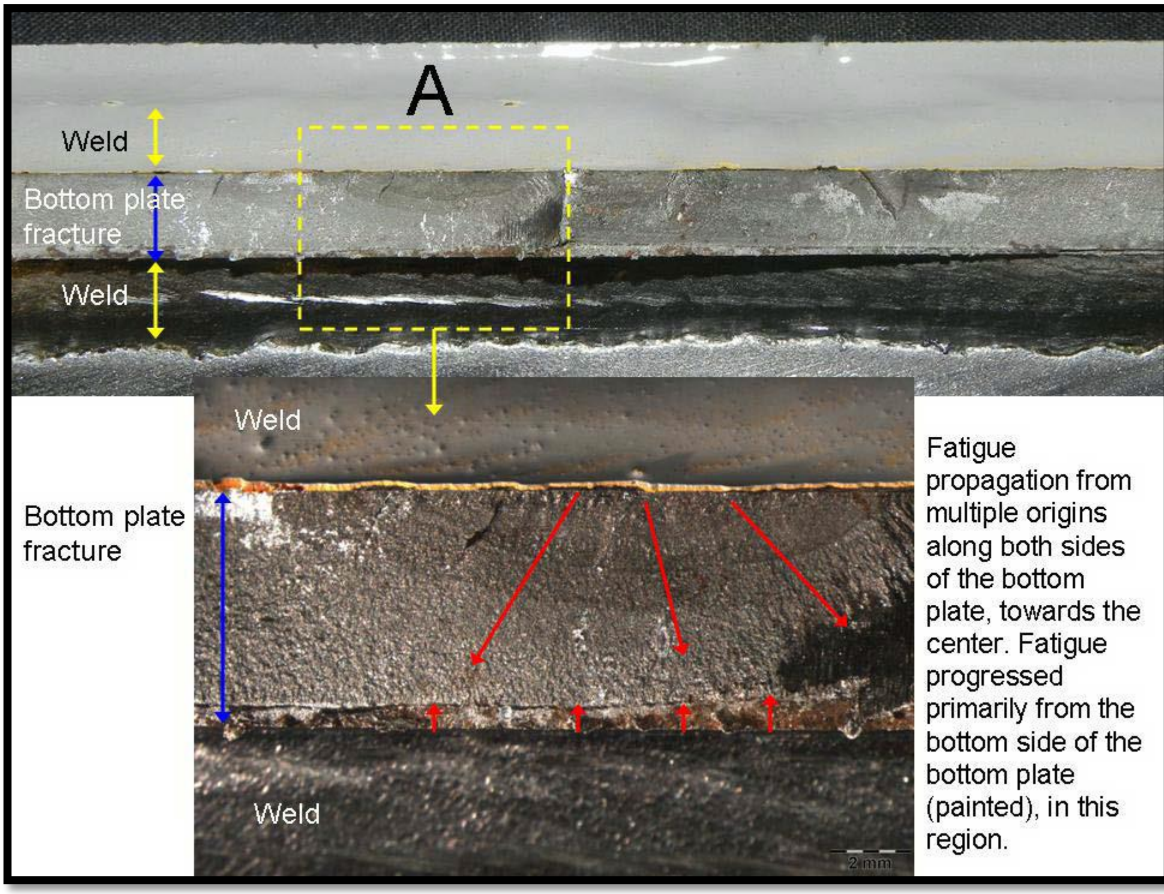

Figure 8: Microscopic View of Fatigue Propagation

Having reviewed the parts, and the failure mode identified, CAT contracted 6DOF to analyze the vibration signature of the failed component on site, and propose a plan to make the oil pan more resistant to the stresses induced from the vibration signatures identified.

Test Results – Round 1

Unfortunately, access limitations did not allow for placing any instrumentation in the oil pan failure region. As shown in Figure 9, the gap between the bottom of the oil pan and the base structure did not provide sufficient space to install any instrumentation.

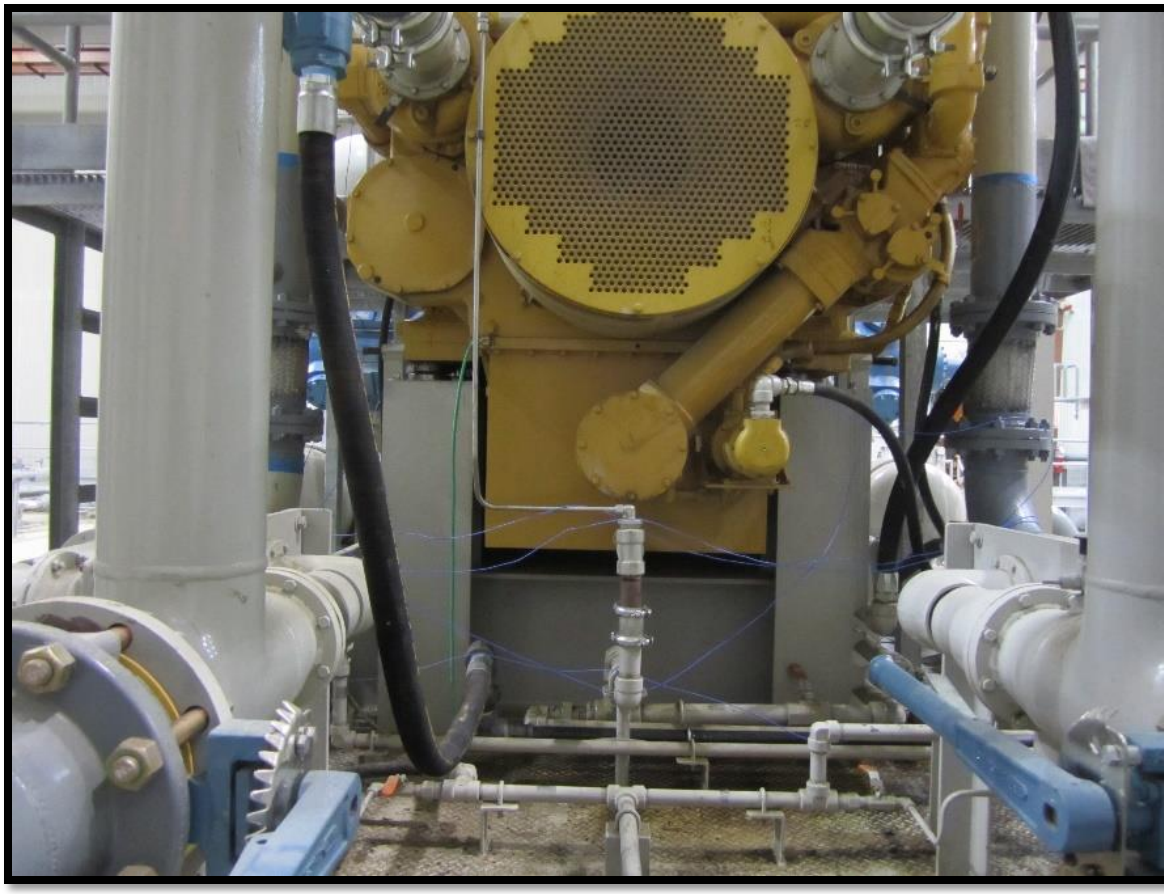

Figure 9: Limited Accessibility of Oil Pan

Standard vibration measurements were made surveying the entire engine, compressor, base system of two CAT 3612's and one CAT 3616 at the location of the first oil pan crack. This allowed for a comparison of units to see if this was a system or unit issue.

In general, the measurements obtained on three different units indicated that the vibration was not particularly high. The primary vibration was at the 1^{st} and 4^{th} orders (multiples of engine-compressor speed). Figure 10 shows the 1^{st} order vibration for the three units and Figure 11 shows the 4^{th} order vibration. Measurements were taken in axial (crank shaft centerline), horizontal (perpendicular to the shaft), and vertical (up and down).

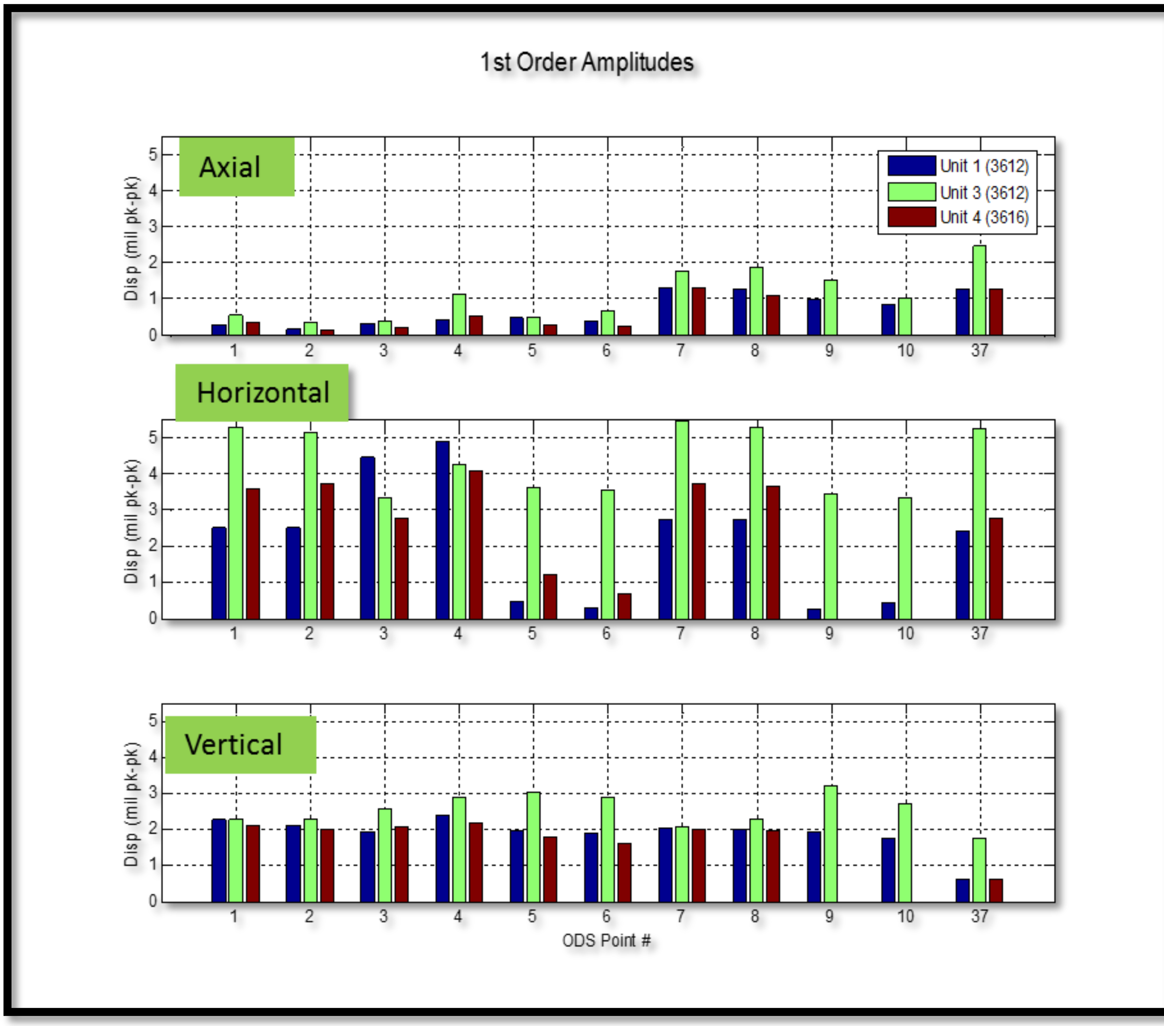

Figure 10: First Order Vibration Measurements on Units 1, 3, and 4

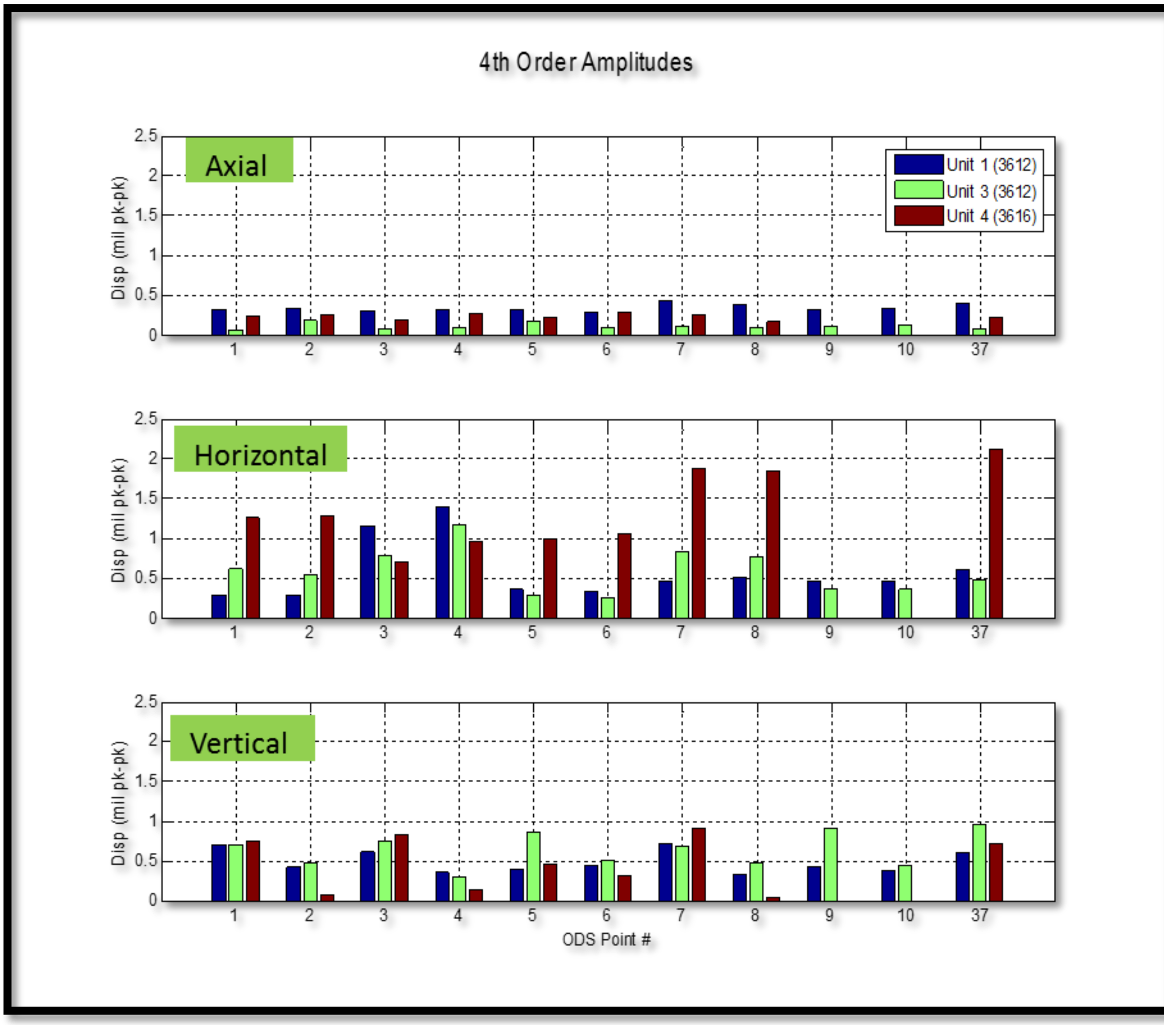

Figure 11: Fourth Order Vibration Measurements on Units 1, 3, and 4

Vibration measurements will typically either be referenced to another instrument or un-referenced. In this situation both types of measurements were taken but the difference between each are important when troubleshooting a vibration related issue.

Phase represents half of the vibration data available to you and can provide insight into the cause or possible solutions for reducing it. In this case, two accelerometers are used to get phase, one as a reference and the other as the measurement point. The phase angle is the position of the peak relative to the reference point. The measuring accelerometer is "roved" along discrete points to create an operating deflection shape (ODS) model. The speed of the unit is swept, from 900 to 1000 RPM to create an illustration of the motion pattern at a particular operating speed and engine-compressor order. The numbered points identify the measurement locations on the package as shown in Figure 12. This allows you to create an animated model to see the direction (phase) of the vibration (motion).

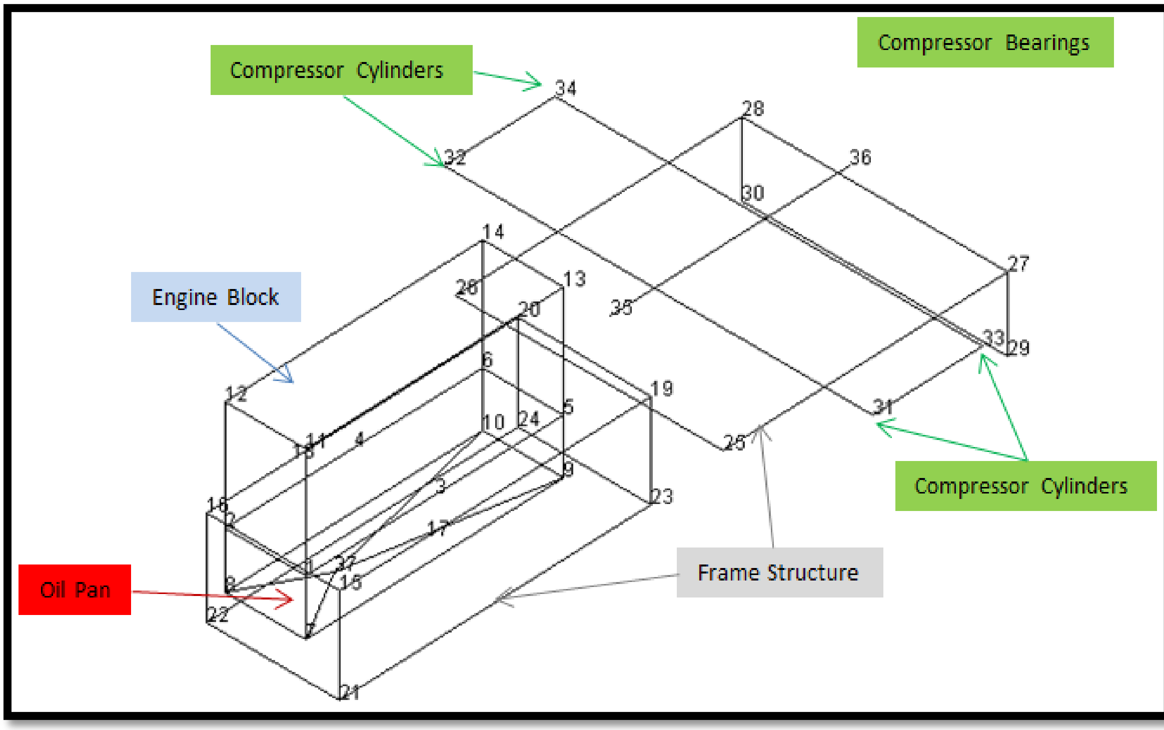

Figure 12: ODS Model of CAT 3612 and Compressor

The ODS were computed from vibration data acquired during speed sweeps. Figure 13 shows a top view of the 1st order ODS for three slightly different engine speeds. The finite element model was used to determine if this motion could cause a stress pattern consistent with the cracking pattern. Although, some system operating deformation shapes looked like they might be related to the pan cracking, no conclusive "smoking gun" was identified.

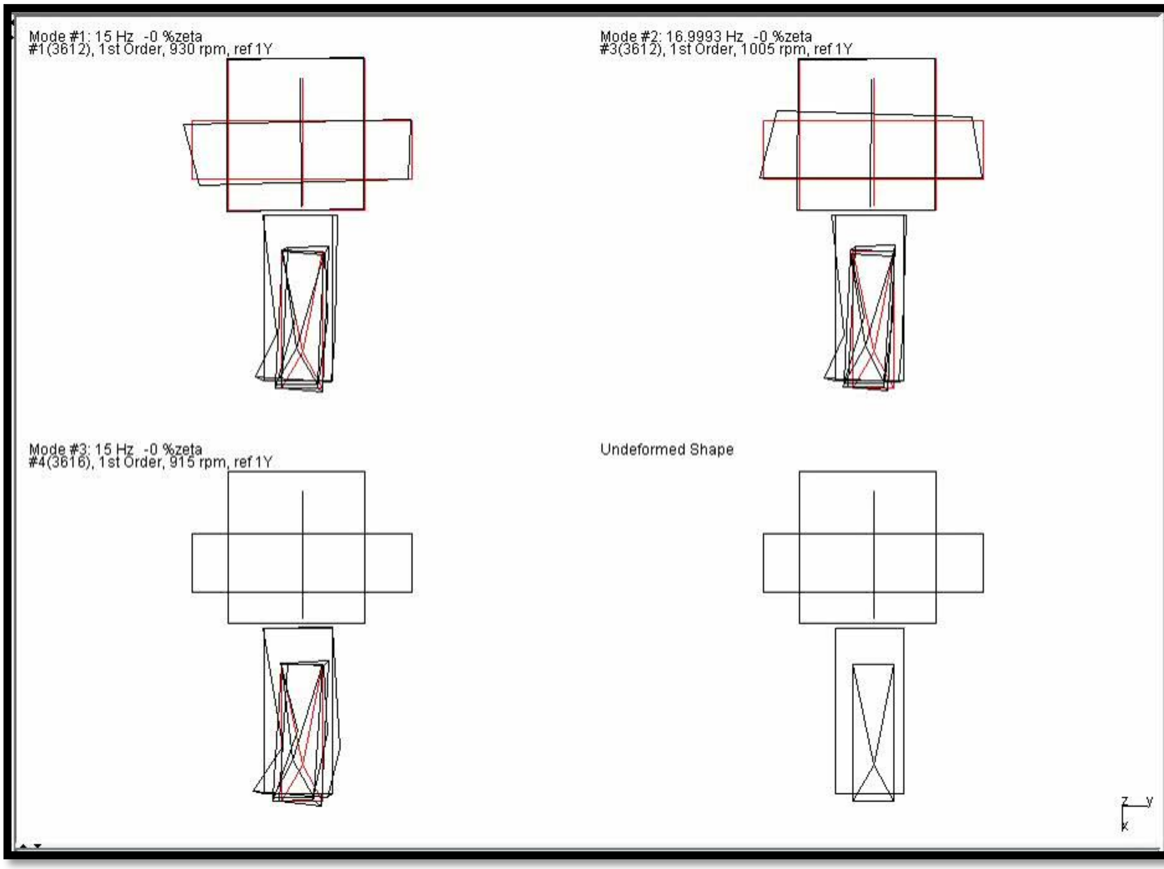

Figure 13: Animated ODS Model

The key result of the first round of testing was that there was not a system wide issue that could cause the oil pan to crack. Rather a more detailed look was required at the local region. To do this, the finite element model (FEM) was reviewed to determine the mode shapes that could cause high dynamic stresses in the orders that were measured during the first round of testing. The FEM would be reviewed to determine strain and measurement locations directly on the oil pan.

Analyses Supporting Root Cause Determination

Finite Element Analysis (FEA) provides a virtual simulation of the structural behavior of a mechanical system. The key components of the system are represented by a very large number of discrete elements. Taken together, these elements combine to provide a model of the mechanical system that represents the overall structural stiffness and mass of the system. This model can be used to predict stresses and structural resonances which are defined by natural frequencies and mode shapes. These mode shapes are the deflection pattern that the structure takes on at each natural frequency.

A finite element model of the oil pan, Figure 14, was developed and incorporated in an overall finite element model of the engine compressor system, Figure 15.

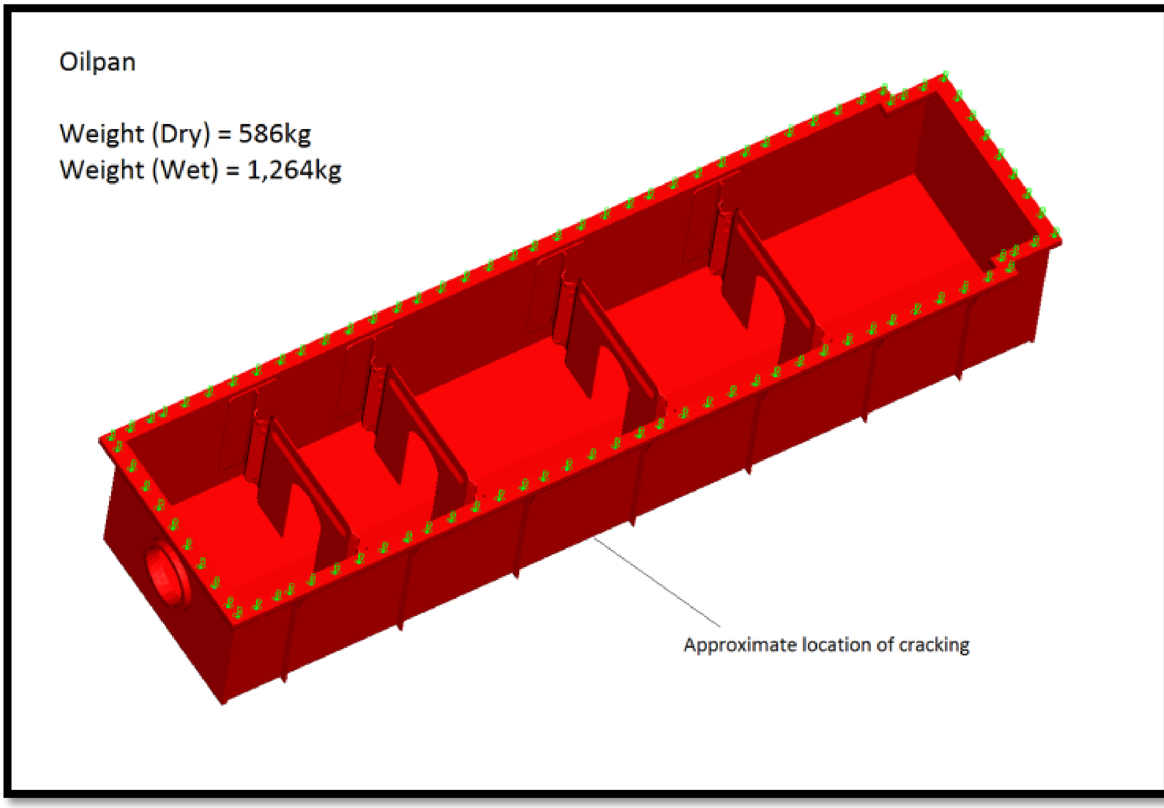

Figure 14: Detailed FEM of Oil Pan

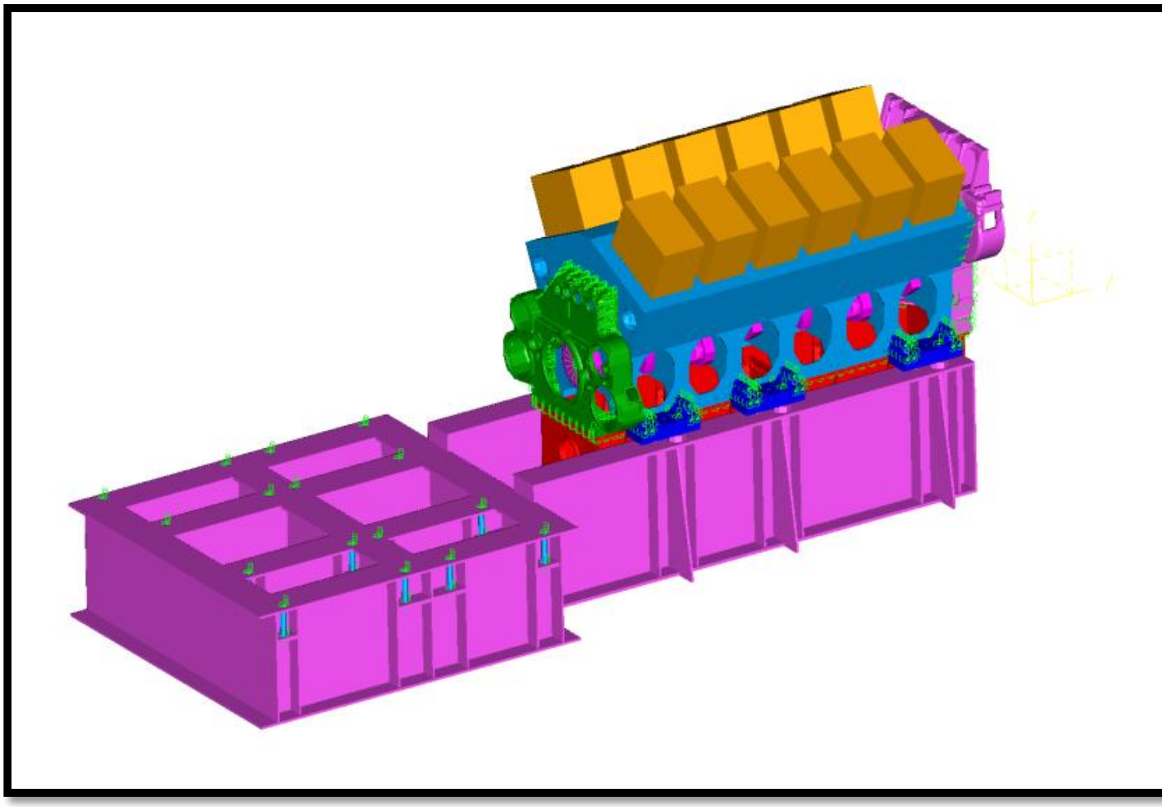

Figure 15: Finite Element Model of a CAT 3612

This model was exercised to apply deformations that were measured in the first round of operational testing. The resulting stress patterns did not match the crack pattern, Figure 16. Once again, this indicated that the issue was not system wide and a closer look at the local mode shape was required.

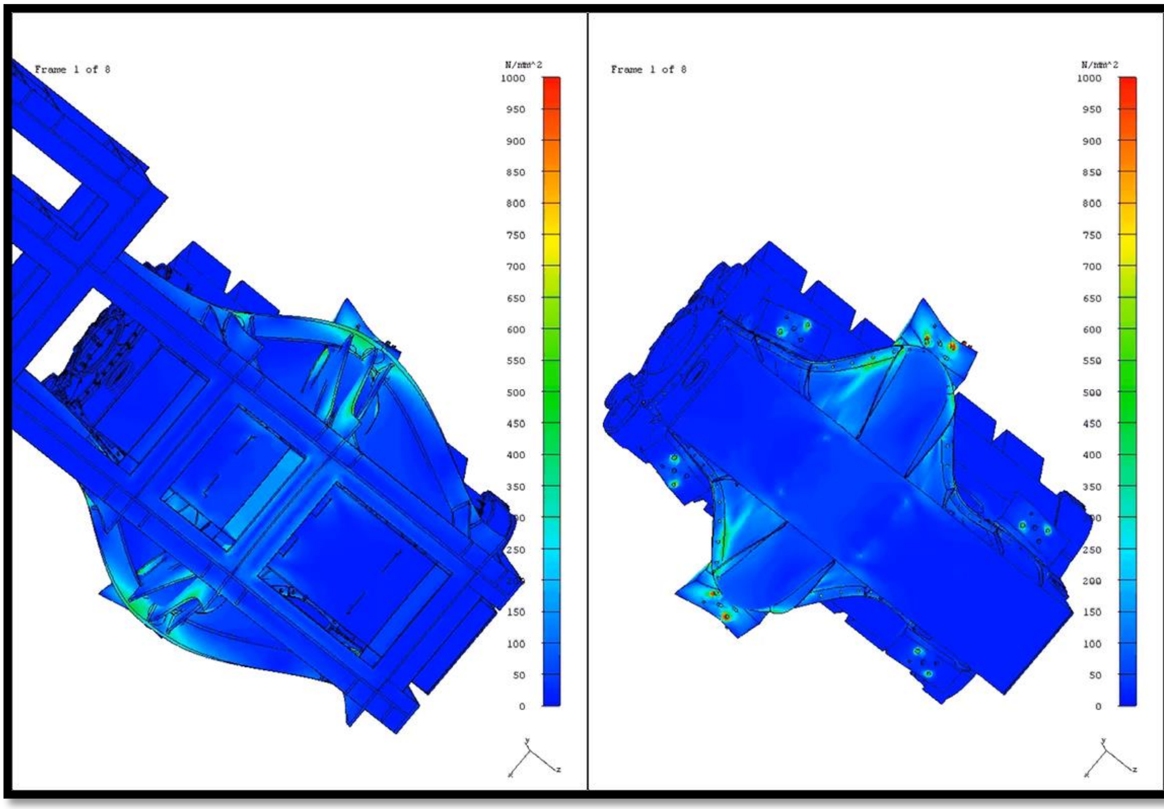

Figure 16: Stress Pattern of CAT 3612 from Operational Test

Further work was done on the oil pan to compute the natural frequencies and mode shapes, Figure 17. One of these mode shapes for the largest oil pan bottom panel matched the crack pattern, Figure 18. The FEA results were used to plan strain gauge and accelerometer locations for further testing. However, it was not yet clear why a particular panel was experiencing a problem. All of the panels exhibited vibration modes that could be potentially excited at various engine speeds. Therefore, it was critical to determine the forcing function exciting the mode shapes.

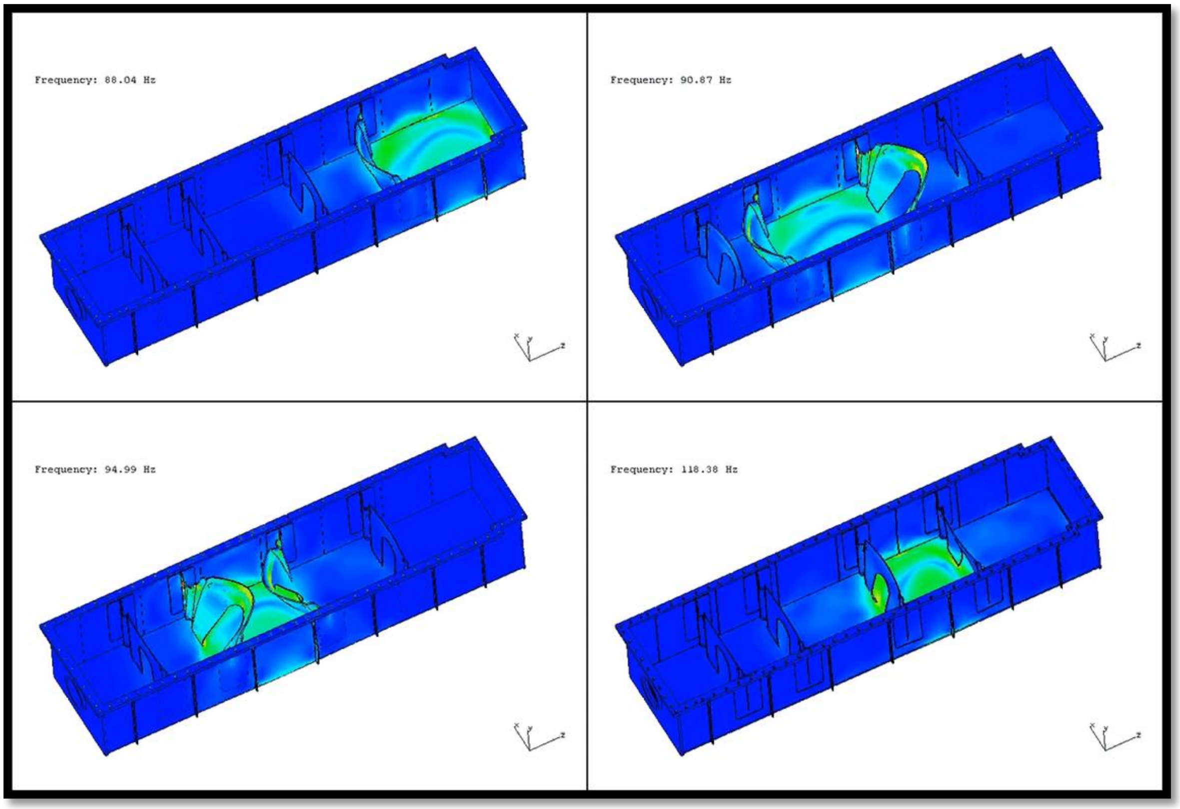

Figure 17: Local Oil Pan-Canning Mode Shapes

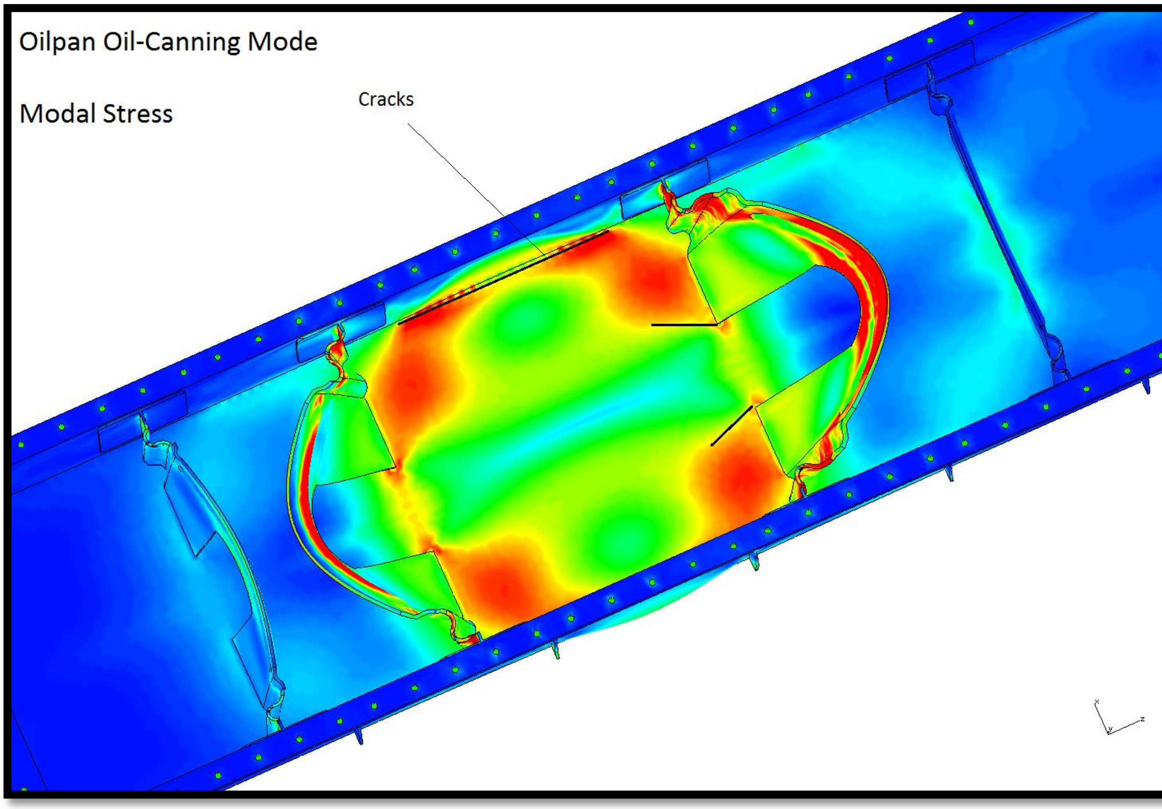

Figure 18: Resultant Stresses from Oil-canning Mode

Test Results – Round 2

The objectives of the 2nd round of testing were aimed at answering the following questions:

What is the strain in the crack area?

What is the frequency of this strain?

What panel or system mode shape is associated with this strain frequency?

What engine or compressor order is providing the forcing function?

Overall, we were trying to understand why the oil pan was failing given the nominal levels of system vibration.

Figure 19 shows the locations on the oil pan where strain gauges were installed. The strain gauges contain a fine wire array bonded to the steel that measure the stretching of the steel by very small resistance changes in the wire. This measured strain is proportional to the resistance produced which can be converted into stresses and related to fatigue life.

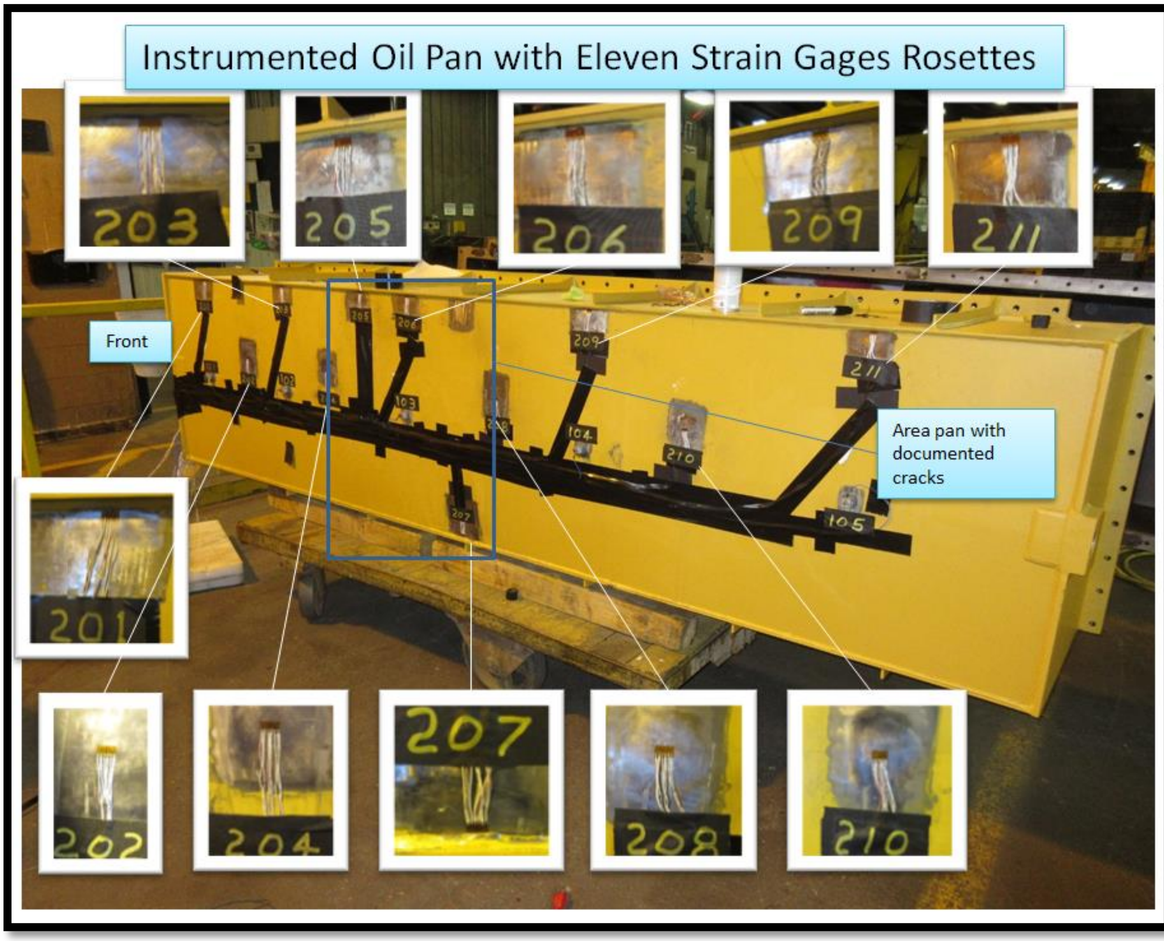

Figure 19: Strain Gauge Locations on the Oil Pan

Figure 20 shows locations on the bottom of the oil pan where accelerometers were installed. Each of the five accelerometers were placed at the center of a panel. Although the bottom of the oil pan was a continuous steel sheet, the bottom of the oil pan could be divided into five somewhat independent panels due to the internal baffles and supports.

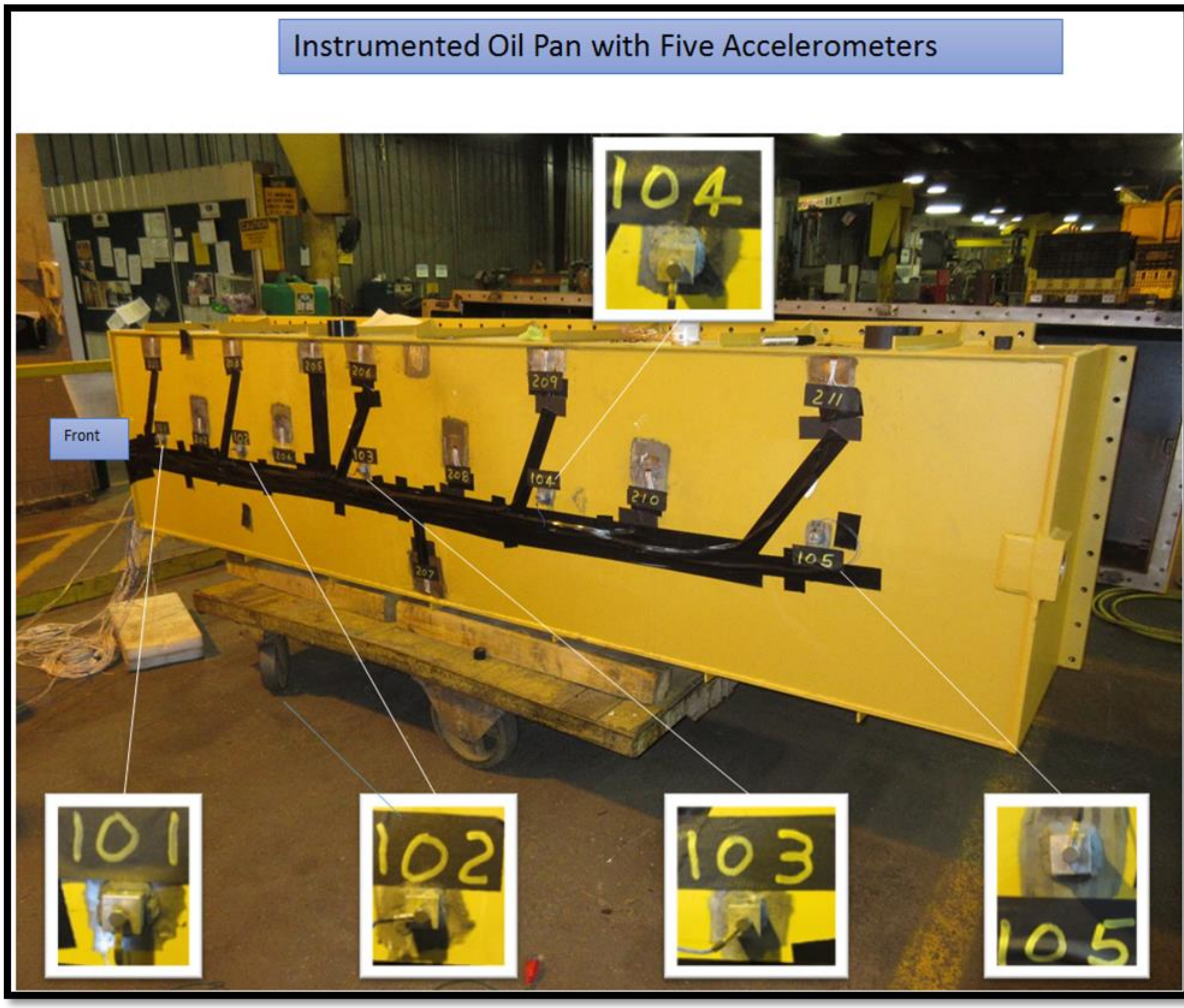

Figure 20: Accelerometer Locations on the Oil Pan

The oil pan was instrumented at the manufacturer's facility and an impact modal test was performed of the oil pan alone, resting on its side. A special hammer incorporating a load cell was used to strike the oil pan. This force was recorded along with the vibratory response of the panel as measured by a very sensitive accelerometer. These measurements are processed to produce the oil pan bottom panels' natural frequencies and mode shapes. Each natural frequency has a unique deflection pattern called a mode shape. These results were compared to the finite element model results of the oil pan.

All bottom panel oil canning (1^{st} fundamental) natural frequencies agreed with the finite element model results except the panel exhibiting the failures, Figure 21. The measured natural frequency of the subject panel was about half that predicted by the FEA. This indicated that this panel had stiffness that was about 25% of what we expected and helped us to understand why there were times the oil pans arrived on site with the panel buckled.

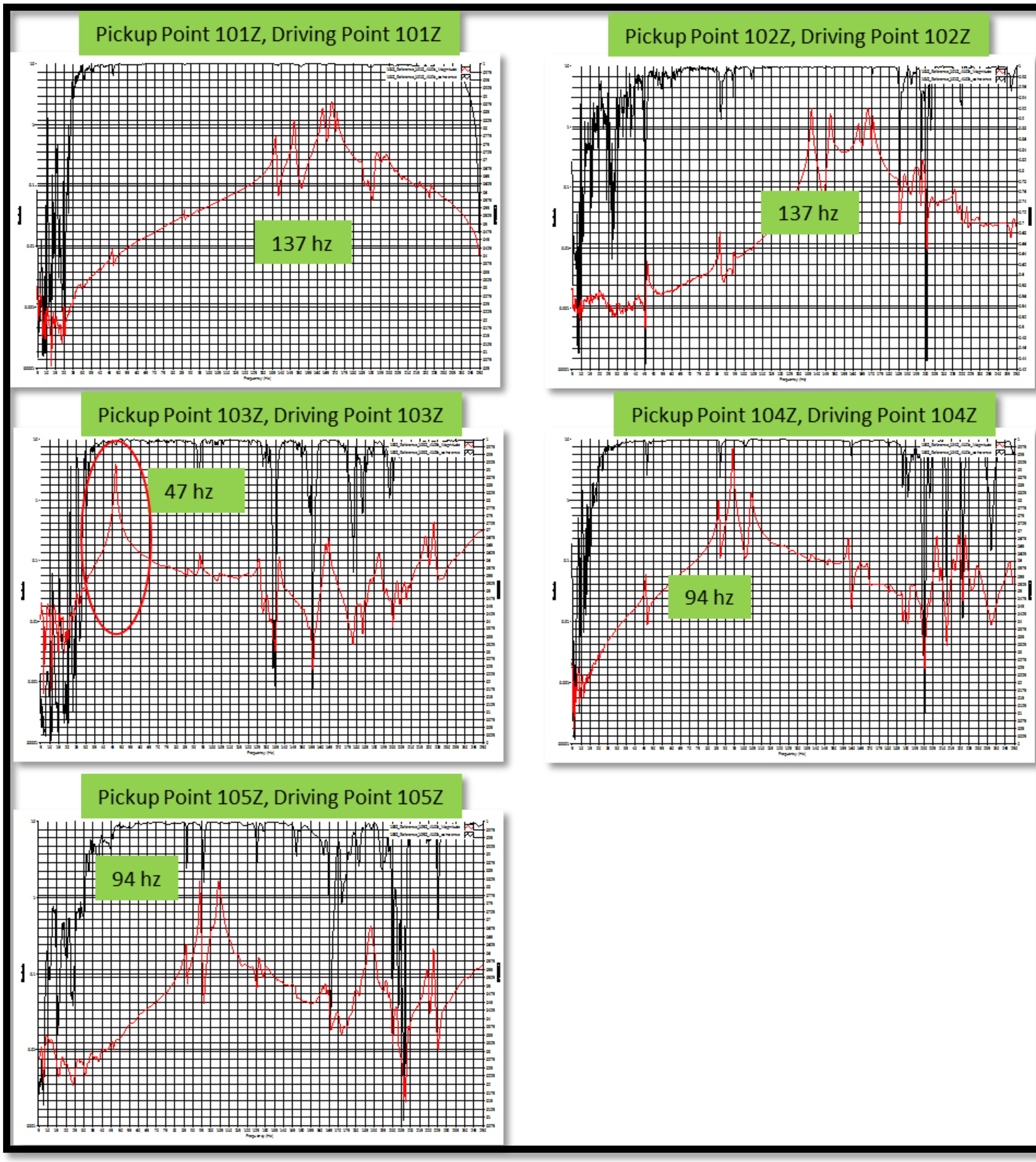

Figure 21: On-site Oil Pan Modal Impact Data

Impact tests were done with the oil pan installed. Data was acquired as the oil pan was filled to determine the effect of the oil mass on the oil pan panel modes. It was found that this was a significant effect and, when the finite element model was adjusted to account for oil mass effects, better agreement was achieved for the cracking panel natural frequencies.

System Vibration Survey

More detailed vibration measurements were made on the compressor, engine, base, and piping structures in order to more thoroughly search for any system level root causes for the oil pan cracking. Figure 22 illustrates the larger array of measurement points used in this round of testing.

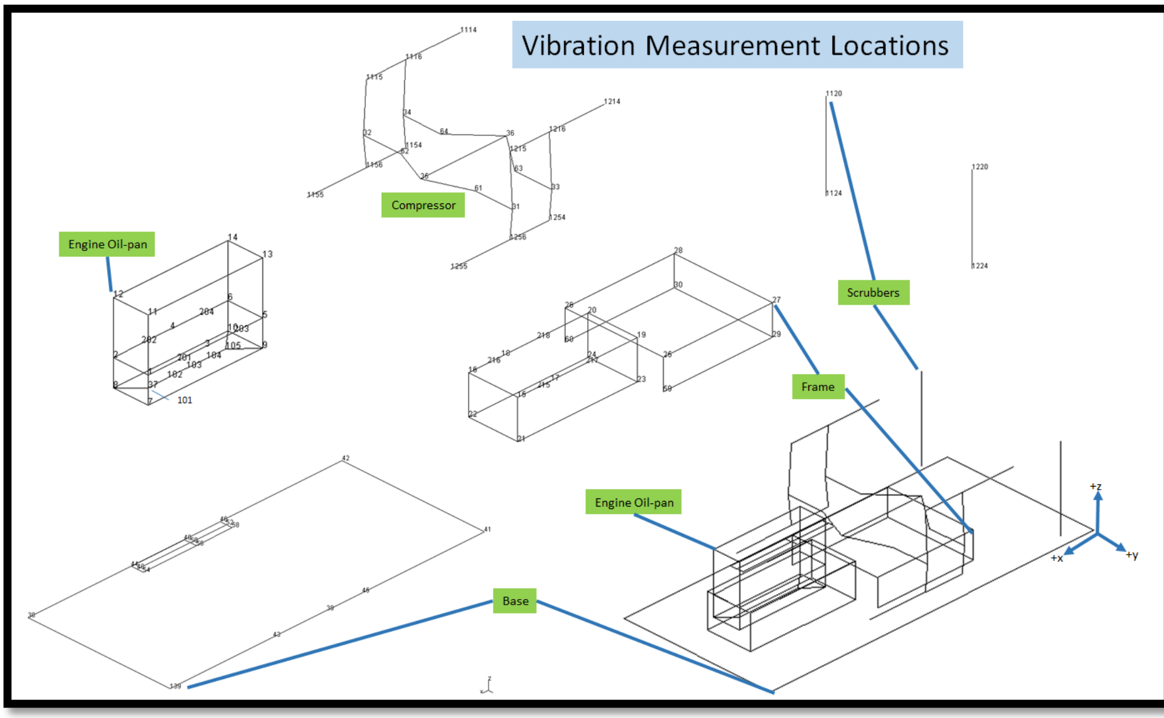

Figure 22: ODS Model of All Measurement Locations

Oil Pan Strain Gauge and Vibration Data

Data was acquired over a full range of engine speeds. This data was processed to provide order tracks of the key engine compressor orders. The key result was that the strain gauges in the failure region showed a strong resonant peak at the 2nd order at about 31 Hz (915 rpm). This resonance caused approximately a 10 to 1 strain magnification factor, Figure 23. Obtaining actual strain data (the strain gauges measure the stretching of the steel which can be related to stress and fatigue life) was a very important addition to the vibration measurements. Vibration data cannot be directly related to the internal stresses of a structure but strains can. The vibration natural frequency causing deformation patterns producing high stresses can be identified by the frequency and magnitude of the measured strains.

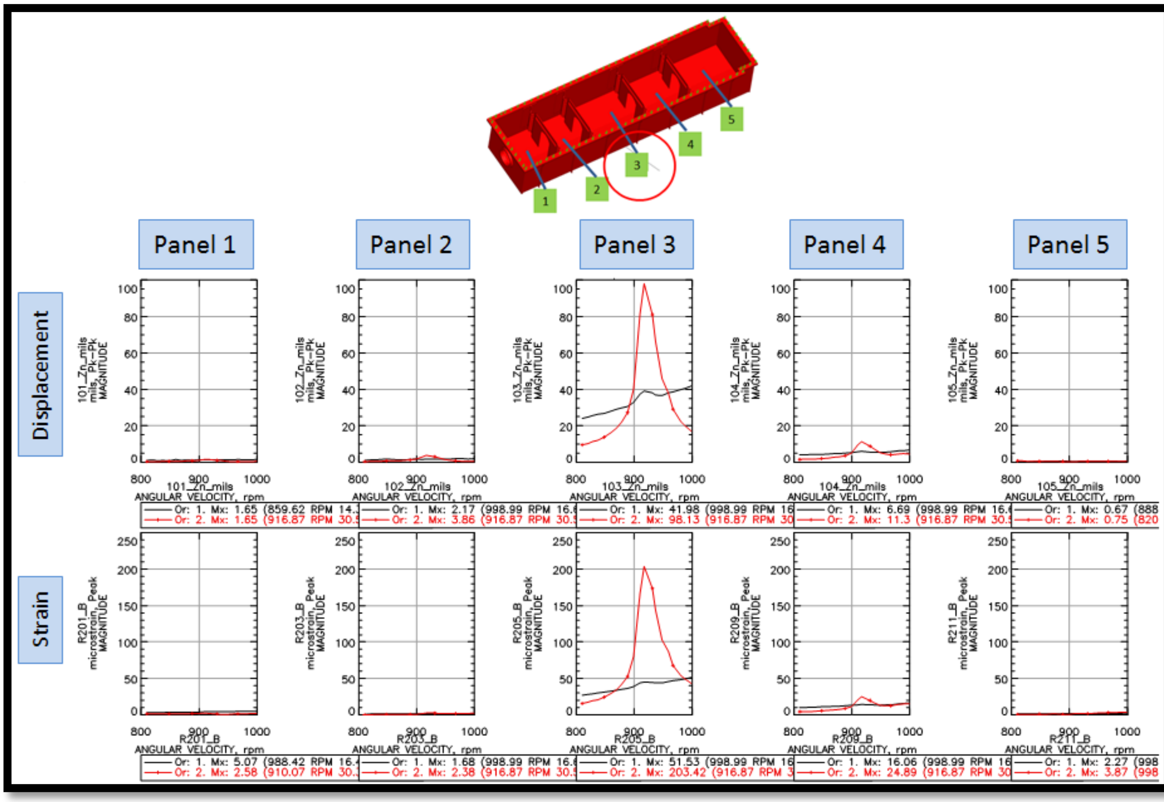

Figure 23: Displacement and Strain Measurements

Once again ODS were developed from the vibration survey data. Of interest was the operating deformation shapes developed from the 2nd order responses. This ODS pattern confirmed that the oil pan cracking was not due to a system wide resonance, but due to a local resonance of the subject oil pan bottom panel. Figure 24 shows the panel motion standing out compared to the motion of the remaining system.

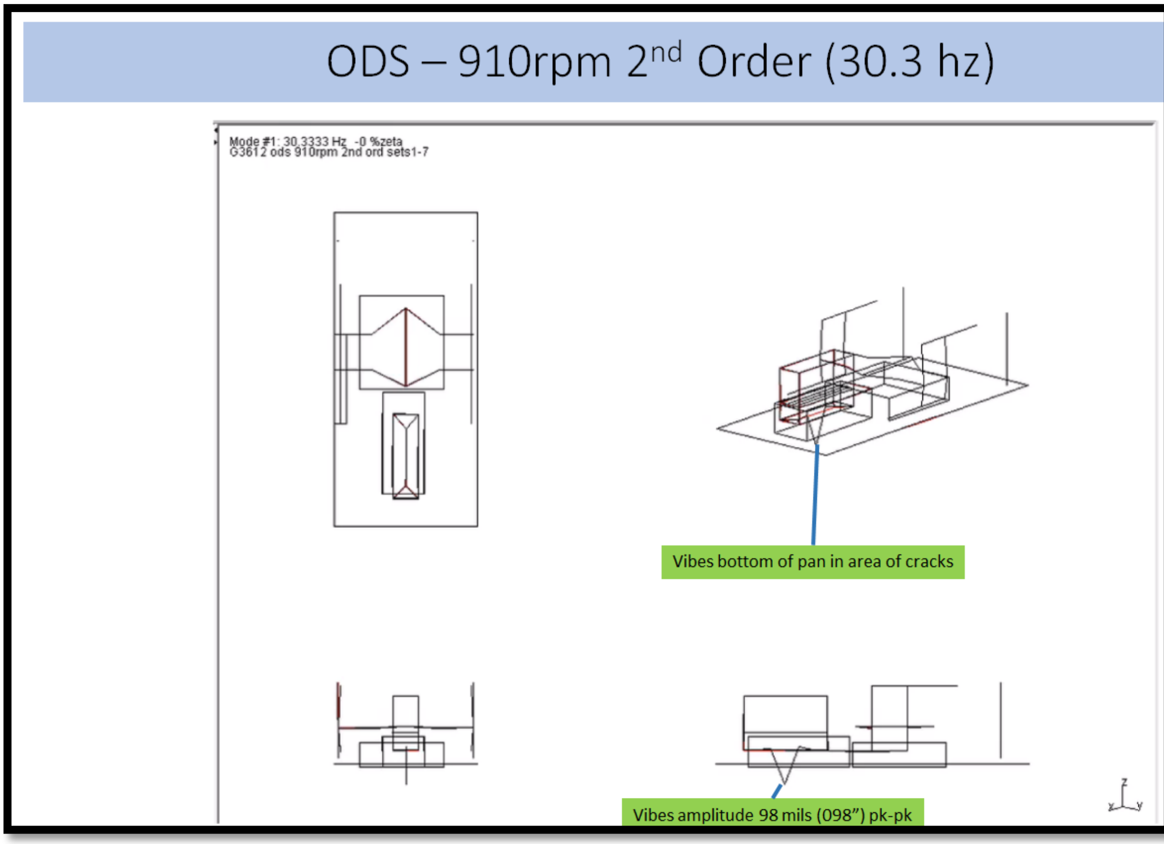

Figure 24: ODS of Oil-Caning Vibration

Figure 25 zooms in on the engine block and oil pan providing a more clear view of the subject oil pan panel motion.

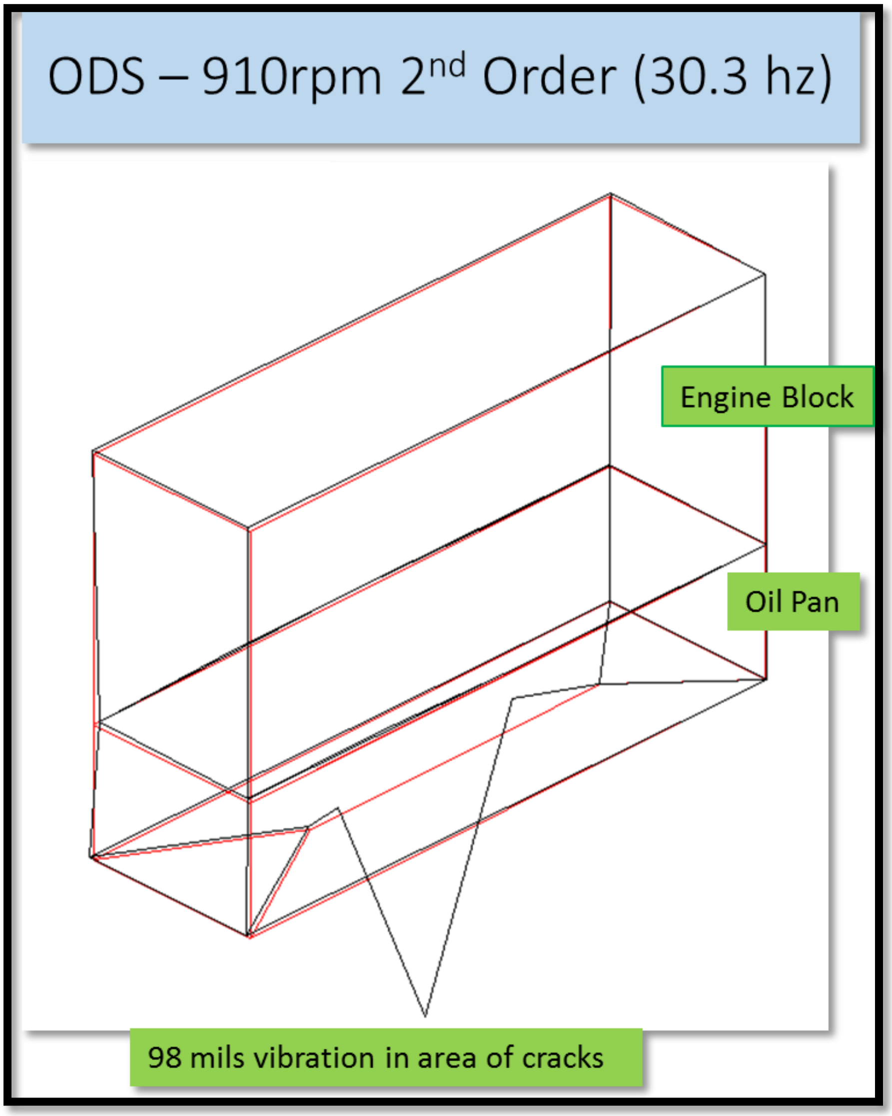

Figure 25: Zoomed in View of Oil Pan Panel Motion

Analysis Supporting Corrective Action

The finite element model of the baseline oil pan was modified with additional stiffeners aimed at increasing the natural frequency of the subject bottom center panel. This analysis included the mass effect of the oil in the oil pan. On-site tests involving the installed instrumented oil pan provided data used to verify this natural frequency. Table 1 presents a comparison of the FEA predicted and test measured natural frequencies for the five bottom oil pan panels. The subject center panel is highlighted in blue. This table also presents the FEA predictions for the modified oil pan as installed with oil. Confidence was gained that the predicted modified oil pan frequency of 69.1 Hz was accurate since the FEA predicted baseline frequency of 35.3 Hz, with oil, compared well to the test measured frequency of 29.0 Hz, with oil.

Table 1: Comparison of Baseline, Test, and FEA Natural Frequencies for the Wet Oil Pan

Wet Oil Pan			
Panel Number	FEA Baseline Oil Pan	Test Baseline Oil Pan	FEA Modified Oil Pan
101	56.2 Hz	62.0 Hz	59.2 Hz
102	62.9 Hz	62.0 Hz	65.2 Hz
103	35.3 Hz	29.0 Hz	69.1 Hz
104	44.4 Hz	46.0 Hz	48.2 Hz
105	33.5 Hz	37.0 Hz	64.7 Hz

Validation Test Results – Round 3

A similar impact modal test was performed on the modified oil pan to determine the bottom panel natural frequencies and mode shapes. This was completed on a standalone oil pan without oil. Table 2 shows a comparison of the baseline FEA and test results and the modified oil pan FEA and test results with the subject center panel highlighted in blue.

The FEA predicted a substantial increase in natural frequency from 90.3 Hz to 164.3 Hz. The impact testing also indicated a substantial increase in natural frequency from 47 Hz to 135 Hz, Figure 26. This provided confidence that the modified oil pan, when installed in the unit and filled with oil, would provide a sufficient increase in frequency and stiffness to eliminate the cracking problem.

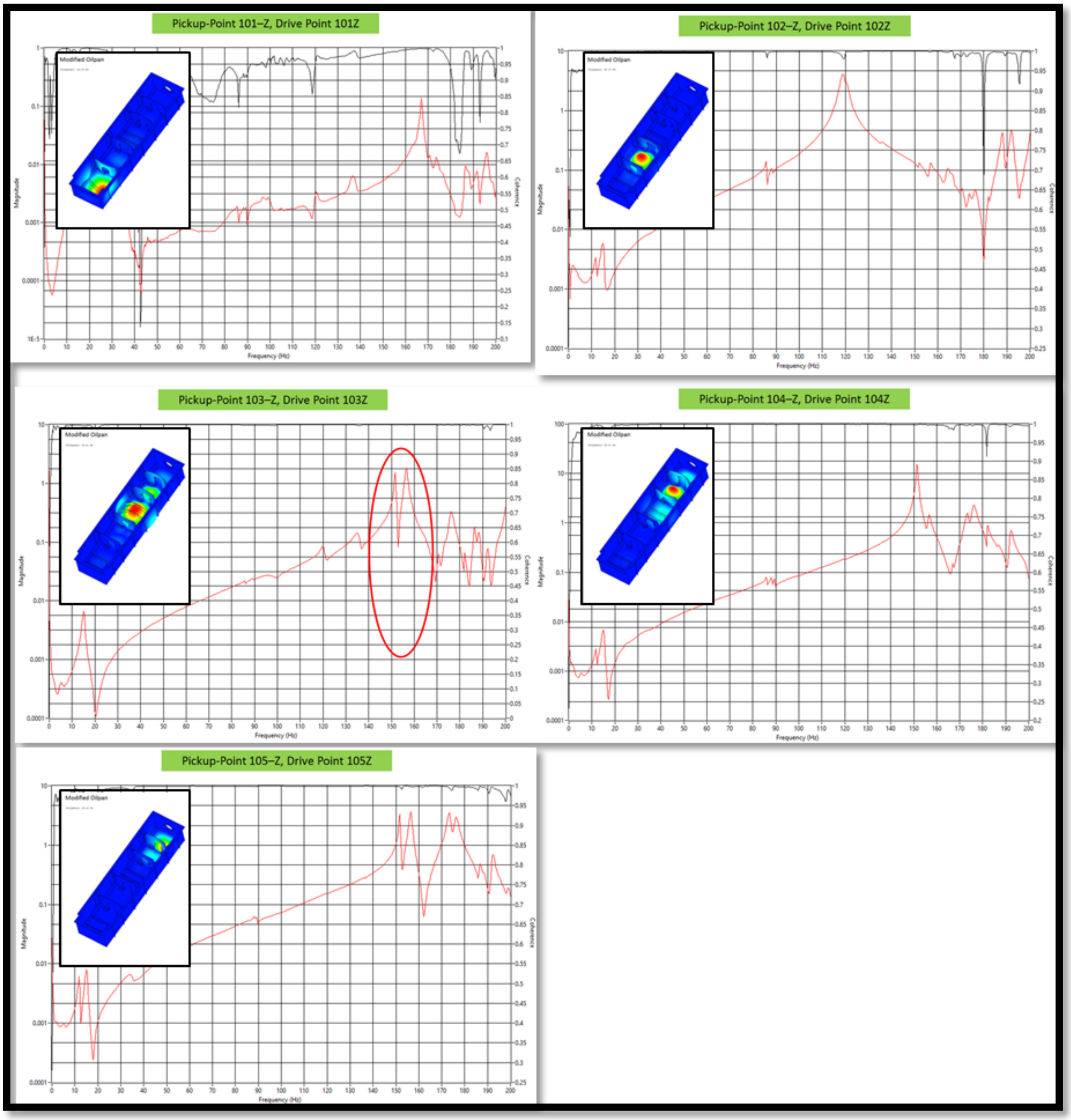

Figure 26: Oil Pan Modal Impact Test After Modification

Table 2: Comparison of the Baseline and Test Natural Frequencies for the Baseline and Modified Oil Pan

Dry Oil Pan - Standalone				
Panel Number	FEA Baseline Oil Pan	Test Baseline Oil Pan	FEA Modified Oil Pan	Test Modified Oil Pan
101	148.1 Hz	137 Hz	167.4 Hz	156.4 Hz
102	>150 Hz	137 Hz	184.6 Hz	151.6 Hz
103	90.3 Hz	47 Hz	164.3 Hz	135.4 Hz
104	117.8 Hz	94 Hz	136.7 Hz	119.0 Hz
105	87.9 Hz	94 Hz	162.8 Hz	165.8 Hz

Conclusions

As shown, the original oil pan (Figure 27) was modified to include internal ribs, gussets, and fit plates to increase the natural frequency of the subject panel, Figure 28 and Figure 29. This additional stiffness moved the mode above the 2nd order forcing frequency. The validation test of the oil pan alone showed that the natural frequencies and stiffness were increased sufficiently to prevent future fatigue failures. This provided sufficient confidence in the solution that an installed, instrumented test of the oil pan would not be necessary.

Figure 27: Original Oil Pan

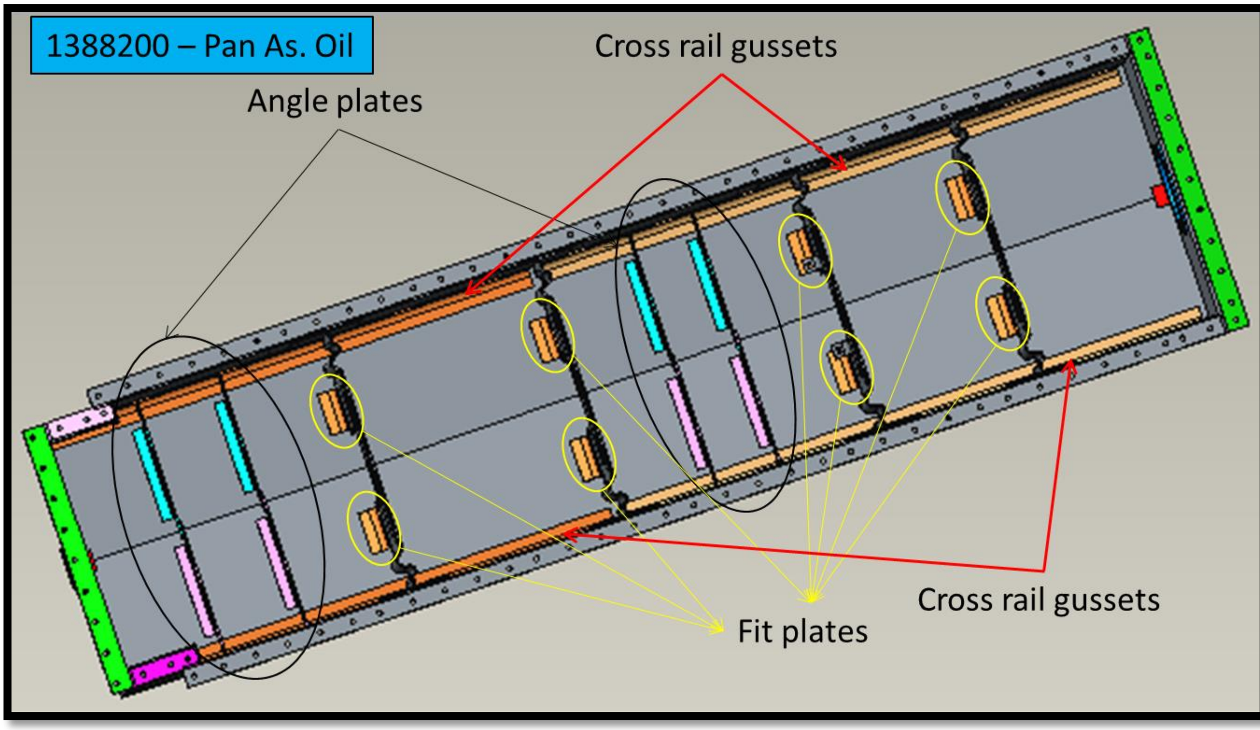

Figure 28: Oil Pan Design with Angle Plates, Fit Plates, and Cross Rail Gussets

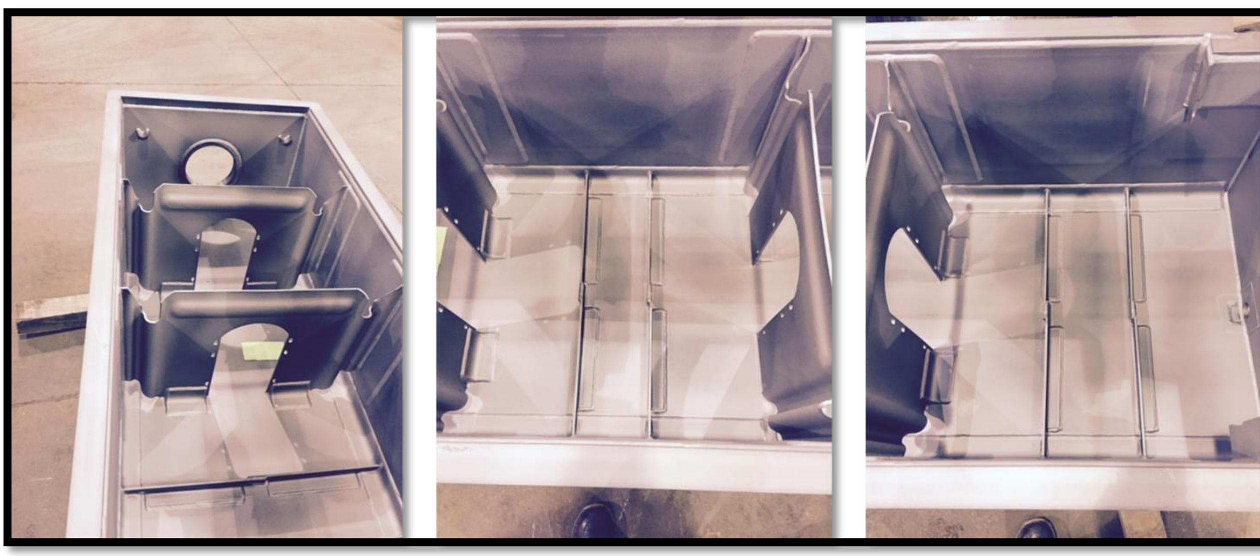

Figure 29: Final Oil Pan with Additional Stiffness and Support in Key Areas