**Vibration Diagnostic Approach Utilizing Finite Element Analysis on Reciprocating Machine for Offshore Facility**

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**Abstract.** This technical presentation focuses on employing Finite Element Analysis (FEA) to investigate the dynamic behaviour of a rotating equipment under continuous vibration due to structural resonance. FEA analysis is employed to visualize and quantify the dynamic response of the compressor under operational conditions. Prior to FEA, and Modal Analysis (MA) was performed to identify the natural frequencies, mode shapes, and damping of the compressor system, providing insights into its structural dynamics. By integrating these techniques, a comprehensive understanding of the compressor's vibration characteristics and potential areas of improvement can be acquired. This can be achieved once a correlation is established between FEA Modal and MA Modal, in which any design modification of Structural Dynamic Modification (SDM) can be done in virtual environment. This presentation will deep dive on how each analysis was demonstrated on a multistage reciprocating compressor package driven by gas engine installed in an offshore facility resulting to improved reliability, integrity, and safety. Employing a structured workflow is key to obtain a feasible resolution on a systemic vibration issue involving resonance and structural integrity deficiencies. The outcome from implementation of remedial solution is also discussed where substantial improvement was seen from the vibration analysis.

**Keywords:** Finite Element Analysis, Modal Analysis, Operating Deflection Shape, Structural Dynamic Modification, Resonance, Natural Frequency, Frequency Response Function

1. **Introduction**

Finite Element Analysis (FEA) and Modal Analysis (MA) are pivotal in resolving complex vibration issues. These techniques have been extensively employed to understand, analyse, and predict the behaviour of structures that have high degree of complexity under various conditions that may contribute to the unwanted situation.

Finite Element Analysis (FEA) is a computational technique used to derive solutions to complex problems in engineering and physical sciences by subdividing a large system into smaller, simpler parts called finite elements. FEA allows for the detailed examination of structural behaviour under various conditions where each element is analysed individually, and the results are aggregated to provide a comprehensive understanding of the entire system. This method is particularly advantageous for analysing structures with irregular geometries, complex material properties, and intricate boundary conditions. Another valuable benefit employing FEA is that it allows a safe experimental modification in a virtual environment which may be dangerous in a physical test situation.

Modal Analysis, a specialized application of FEA focuses in determining the vibration characteristic of a machine or structure. This analysis identifies the mode shapes and natural frequencies, which is paramount to understand how a structure responds to dynamic loading conditions (i.e. vibrations, shocks, and oscillations). By identifying these parameters, engineers can predict resonance conditions and avoid potential failures due to excessive vibrations.

The integration of FEA and Modal Analysis plays a significant role in modern engineering design and analysis. These techniques are used across various industries where complex structural issues is impacting the asset reliability and plant performance. By providing detailed insights into the behaviour of materials and structures, FEA and Modal Analysis facilitate the development of groundbreaking solutions to difficult engineering challenges.

**Operating Deflection Shape (ODS)**

ODS analysis is a technique that was routinely used since mid-1980s to assist engineers and vibration analysts in vibration problem identification and solution development. Since ODS is a subset of Experimental Modal Analysis (EMA) technique, this method was employed to derive Frequency Response Function (FRF) to generate mass, stiffness, and damping properties, in which ODS modelling developed in virtual environment can produce the natural frequency mode shape and its response; hence making structural modification possible in various ways.

The ODS procedure involves generation of a geometric representation of the machine or structure, selection of test point locations, acquisition of data, and animation of results. The model typically begins with a simple geometric shapes or lines to be denoted as an object. For higher accuracy of results, the model shall be as close as possible to the actual machine and structural geometry focusing on vibrating and support components. For an example in this case study, a Reciprocating Compressor shall include the compressor frame, cylinders, distant piece(s), crosshead housing, and pulsation bottles. The baseplate is another paramount element to be included in the modelling as all individual equipment (Driver, driven, and power transmission) are installed on a single structure plate.

Once the vibration spectrum and phase reference obtained during a routine survey and uploaded into the modelling, FRF can be applied to determine the machine dynamic characteristics where Natural Frequency, Mode Shapes, and Damping features.

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| A drawing of a cube  Description automatically generated |
| **Figure 1.** Operating Deflection Shape (ODS) Model |

1. **Background & Equipment Overview**

This technical paper focuses on the advanced vibration diagnostic approach performed on a reciprocating compressor driven by natural gas engine at a remote offshore location. The said offshore facility, normally unmanned during operation equipped with high pressure gas lift facility have been in operation for more than 20 years.

All compressors, namely Unit-A, Unit-B, and Unit-C comprises of 2 stage reciprocating compressor driven by a natural gas engine with Reduction Gearbox for stepping down the driver speed. A graphical representation of machine configuration is as per **Figure 2** below:

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| **A diagram of a process  Description automatically generated** |
| **Figure 2.** Two Stage Reciprocating Compressor Train Configuration |

All three (3) compressor units are equipped with pulsation dampener bottles for each stage suction and discharge side, located above and under the compressor cylinder to stabilize the gas flow and reduce vibrations. At the head end of each compressor cylinders, there is a fixed clearance pocket where it can be manually adjusted to regulate the compressor flow throughput. Throughout this compressor operating regime, the pocket has been completely flushed thus maximizing the outflow flow to get maximum gaslift volume.

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| **Figure 3.** Cross-section of Reciprocating Compressor and Components  Source: [I (wordpress.com)](https://jensapardi.wordpress.com/wp-content/uploads/2010/02/reciprocating_compressor4.pdf) |

The compressor driver is a V-type 16-cylinder Turbocharged Aspirated-Aftercooled engine producing 930 horsepower (at 1,200 rpm) with a hydraulic powered starting system. The engine has been regularly maintained in accordance to the required Maintenance Schedule as stipulated by the Manufacturer. Speed of operation by the driver ranges from 800 rpm to 1,200 rpm where it can be manually regulated via Local Control Panel or put in Auto Mode. Each engine is coupled to a speed reducer with a gear ratio of 3.194:1 to further reduce the compressor frame speed to its rated speed.

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| **Figure 4.** 16-Cylinder Turbocharged Aftercooled Natural Gas Engine  Source: [G399specsheet.pdf (swiftequipment.com)](https://swiftequipment.com/Images/Engines/102233/G399specsheet.pdf) |

1. **Event Timeline**

The historical failure will be further discussed in this Section, where it all began during the change implementation of operating philosophy for the gaslift compressors from 3 X 50% to 3 X 33.3%. The changes took place to further increase the platform production by increasing the gaslift volume to be reinjected to gaslifted wells, hence increasing the oil production.

The first compressor failure detected on Unit-C after several days in operation with the new operating philosophy change implemented. During the failure event, Unit-C exhibited knocking sound from first stage cylinder and eventually compressor tripped without indication. The inspection team deployed to perform thorough inspection and found the first stage piston was broken with large material wreckage from the piston inside the cylinder. Traces of liquid was also evident, signifying the presence of liquid carryover from compressor suction scrubber.

The compressor had to undergo a complete overhaul on the affected cylinder before being put back to operation by utilizing a spare piston assembly to replace the damaged piston. Once Unit-C completed the overhauling activity, unit was put back online for another start-up attempt with presence of Vibration Survey personnel to perform the routine survey of the compressor with new piston. The compressor was put on load with engine speed at 1100rpm, and significant floor vibration witnessed by all personnel onboard during the test run. After several hours of running with load condition, similar Failure Mode observed (knocking sound from first stage cylinder) during Operations walkabout surveillance and decided to manually shutdown the unit to authorize another inspection activity.

The second inspection carried out by the Frontline Maintenance Team revealed that similar Failure Mechanism happened on the first stage piston assembly, but without traces of liquid carryover. Other additional findings recorded during the inspection was the piston nut found loose and not securing the 2-piece piston in the assembly.

The summarized Sequence of Events (SOE) can be referred to **Figure 5** below.

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| **Figure 5.** Compressor Unit-C failure Sequence Of Events |

Summary of vibration survey results also compared as below (**Figure 6.**). Note that the previous reading represents the initial vibration reading before the new operating philosophy took place, while the current values denote the vibration reading after the changes were implemented.

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| **Figure 6.** Compressor Unit-C increase in vibration trending |

1. **Root Cause Analysis**

The compressor experienced multiple failures on identical Failure Modes, particularly on Unit-C have impacted the overall oil production as it was primarily used for gaslift wells. This has called for Root Cause Analysis (RCA) to be employed to determine the causal factor and to identify the remedial actions. A dedicated RCA team was assembled consist of a technical team leader, subject matter experts, operation & maintenance personnels and other related key contributors to resolve the issue.

The problem statement was agreed upon, leading to 4 possible root causes as displayed in **Figure 7**. For the interest of discussion focusing on Finite Element Analysis, ‘Piston Half not Intact’ failure mode will be evaluated while the remaining causal factors will not be discussed in this technical paper.

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| **Figure 7.** Root Cause Analysis tree for Unit-C |

Analysis above suggests that the machine running frequency is operating close to structural natural frequency, hence amplifying the vibration levels as induced by the machine to the support structures which will be discussed further in the following section. This phenomenon is also known as Resonance.

1. **Methodologies**

The methodology application employs six (6) steps in resolving the Resonance issue.

* 1. *Structural Skid Bump Test*

To begin with Finite Element Analysis, the existing machine and structural natural frequencies need to be determined. This can be achieved using ‘Impact Hammer’ by providing a known force excitation to a structure. Through this process, the resulting vibrations are measured to establish the structure natural frequency, damping, and mode shapes.

Precaution should be considered while performing this activity where the impact force applied on the hammer to the structure or component must not vary too much as it will influence the resultant vibration signatures.

* 1. *Generate Finite Element Analysis (FEA) and Frequency Response Function (FRF) Modal Analysis*

Utilizing the actual equipment dimension, mechanical assembly details, and material specification, a Finite Element Model was generated using applicable software. In some situations where information is not completely available, assumptions can be made to complete the model, but the resulting analysis will be impacted if the assumptions used are too far off from the actual data. For instance, some geometry parameters of the machinery skid under the structure floor are not accessible and since no available drawing to be used as reference, Engineering assumptions to be employed in the FEA model.

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| **Figure 8.** Finite Element model for Unit-C |

Vibration signals collected using the impact hammer was then converted from time domain to frequency domain (via Fast-Fourier Transform-FFT) to develop a mathematical model to be incorporated in the FEA model to describe how a structure or mechanical component responds to excitation forces. This method, also known as Frequency Response Function (FRF) Modal Analysis provides an insight of how the mechanical system behaves under dynamic forces across different frequency excitations. The resulting model will provide valuable information such as the Natural Frequencies, Mode Shapes, and Damping characteristics.

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| **Figure 9.** Example of FRF knock response in horizontal (X-axis) and vertical (Y-axis) direction on Gas Engine | |

*5.3 Resonance Verification*

FEA model was verified by FRF Modal Analysis in terms of mode shapes and its corresponding natural frequency. This indicates that FEA model was accurate enough and can be used for performing Structural Dynamic Modification (SDM) virtually in computer environment. This minimizes forms of “trial-and-error” solution on the actual structure. Both FRF and FE Modal Analysis results are correlated and summarized in **Table 1**.

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| **Table 1.** FEA and FRF comparison for Unit-C | | | |
| **MODE** | **FEA** | **FRF** | **REMARKS** |
| Scrubber Bending (Y-axis) | 16.7 Hz | 14.5 Hz | Local Mode |
| Scrubber Bending (X-axis) | 21.3 Hz | 22.0 Hz | Local Mode |
| **Engine Sliding Mode (Y-axis)** | **19.4 Hz** | **19.5 Hz** | **Local Mode** |
| Skid Bending Mode | 22.8 Hz | 23.0 Hz | Global Mode |
| Gearbox Bending (X-axis) | 36.7 Hz | 38.0 Hz | Local Mode |
| Gearbox Bending (Y-axis) | 40.5 Hz | 42.0 Hz | Local Mode |

Both FEA and FRF Modal analyses revealed that at engine, a horizontal mode is observed at 19.5Hz which is very near to the running speed of engine at 18.5Hz (5% separation margin). This explains high vibration registered at engine in horizontal direction and this has probably caused high relative movement on the idler shaft and eventually damages the coupling gear. In short, the engine is considered dynamically weak, and this can be classified as NEAR RESONANCE problem.  
  
Referencing to *API Standard 618: Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services 5th Edition (Reaffirmed, August 2016)*; guidelines in mechanical design and vibration analysis for reciprocating engine and compressor as below:

Clause 7.9.4.2.5.3.2 Separation Margins:   
(a) The minimum mechanical natural frequency of any compressor or piping system element shall be designed to be greater than 2.4 times maximum rated speed.  
(b) The predicted mechanical natural frequencies shall be designed to be separated from significant excitation frequencies by at least 20%.

* 1. *Structural Dynamic Modification (SDM)*

As the contributary cause for resonance have been identified, alteration to existing structural dynamic characteristics can be made in a virtual environment. This allows Analysts to perform experimental modification without having to perform the physical modifications yet through Structural Dynamic Modification (SDM).

In this FEA, Structural Dynamic Modification (SDM) refers to shifting the natural frequencies away from the excitation frequencies by adding, removing, or modify the existing structural geometry. Nevertheless, shifting the natural frequency greater than 2.4 times the rated speed (>44.4Hz) will involve major modification which is impossible in this case. Therefore, SDM will only focus on shifting the natural frequency away from ±20% of operating speed (1110rpm or 18.5Hz) which are <14.8Hz or >22.2Hz.

**Figure 10** below summarizes the potential modification to achieve the requirements of API Standard 618 for Engine Sliding Mode Natural Frequency of 19.4 Hz:

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| No. | Modification Description | FEA | SDM | Margin |
| SDM #1 | Adding triangle fins support to all engine support (6 nos) | 19.4 Hz | 18.9 Hz | -2% |
| SDM #2 | Adding 2 back-to-back L-bar along existing engine support C-channel | 19.4 Hz | 19.6 Hz | +0.5% |
| SDM #3 | Adding two(2) L-bar along existing engine support C-channel | 19.4 Hz | 22.5 Hz | +16% |
| SDM #4 | Adding 15 rectangular (15mm thick) support along engine support C-channel | 19.4 Hz | 27.9 Hz | +44% |
| SDM #5 | Adding 4 L-bar (90X90) to link the existing C-channels underneath the engine | 19.4 Hz | 23.0 Hz | +18% |
| **Figure 10.** SDM Results and comparison with existing FEA Natural Frequency on Engine | | | | |

* 1. *Execution*

As summarized, **Figure 10** clearly indicates that SDM #4 as the only modification that meets the API Standard 618 requirements of >20% Natural Frequency separation margin. Another additional advantage of SDM #4 is on the feasibility and practicality to execute the physical modification as below:

1. Hot work (welding) can be performed during platform Turnaround since Unit-C gas engine is due for Major Overhaul maintenance program.
2. Low modification complexity on SDM #4 due to easy access to engine C-channel with minimum physical access restrictions.
3. Low in overall modification cost.

With above justifications, SDM #4 have been selected as the modification of choice to be executed with highest probability of shifting the natural frequency away from engine operating speed.

* 1. *Post Modification Validation*

Modification of SDM #4 on Unit-C was evaluated during the initial unit start-up with 100% compressor load shows significant reduction on high frequency harmonics (> 2X engine and compressor frequencies) with overall vibration registered at less than 5mm/sec peak. However, FRF Modal Analysis at Engine Y-axis did not show significant improvement with regards to shifting the Natural Frequency away from running frequency.

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| Pre-Modification | Post-Modification |
| Vibration harmonics (Pre) | Vibration harmonics (Post) |
| FRF Modal (Pre) | FRF Modal (Post) |
| **Figure 11.** Comparison of vibration and FRF result - Pre & Post modification | |

Even though the overall vibration has been reduced, the team have decided to analyse further on the result which not completely meeting the overall objective.

1. **Outcome and Discussions**

Modification of engine structural support resulted to significant shift of natural frequency by 44% as simulated in a virtual environment via simulation. However, the result did not fully achieve its objective where the FRF Modal indicates similar fashion between pre and post modification despite the overall vibration magnitude reduction to less than 5 mm/sec peak.

The analysis team discovered that there was inaccuracy of initial FEA modelling where engine support beams not considered during the model development stage. This happened due to the inaccessibility of compressor skid underneath during the work scoping activities with no detailed General Arrangement drawing available. The actual engine support beams as identified in **Figure 12** added to the FEA model for the next simulation.

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| FEA Modelling | Modification to FEA Modelling |
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| **Figure 12:** Engine support structure verification | |

Besides attention to engineering details, reasonable tolerances and assumptions must be carefully addressed in developing the most accurate FEA model and reduce the risk of engineering errors.

Despite the challenges and upsetting result, the modification has been instrumental in reducing the overall vibration of the engine and reducing the risk of high frequency impact towards compressor.

1. **Conclusion**

Finite Element Analysis is a powerful tool in resolving complex vibration problems, especially when it comes to Resonance related issues. From this case study, it was evident that structural modification and strengthening is required to shift the natural frequency away from the running frequency of the machine. This can be performed as discussed in Section 5 of this technical paper by employing six (6) critical steps; from identifying the pain points, zooming into the causal factor, and Engineering execution until complete resolution of the issue.

Operating Deflection Shape (ODS) model allows machine analysts to perform various kind of modification without having to perform the physical alteration, thus providing better prospect in selecting the most feasible and practicable solution at minimum risk and cost effective.

A handful of Discipline Lead key collaborators usually required to ensure successful project execution. For this specific case study, a multi-discipline team consists of Mechanical Rotating, Civil & Structure, Piping, Turnaround Team, Operations, Higher Learning of Institution, and Construction Service Providers have been gathered to collectively cooperate and contribute to resolve complex vibration issue.

1. **References**

[1] American Petroleum Institute. “Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services, Fifth Edition, Reaffirmed August 2016.” *Pulsation and Vibration Control*: 72

[2] Eng Hoe Cheng, Dr Abdul Ghaffar Abdul Rahman “Finite Element Analysis of Unit-C Gaslift Reciprocating Compressor” *MDTQ2/RQA/20110726*

[3] D. J. Ewins, Modal Testing: Theory and Practice, Research Studies Press, LTD, 1984

[4] Reciprocating Compressor “<https://jensapardi.wordpress.com/wp-content/uploads/2010/02/reciprocating_compressor4.pdf>”

[5] Caterpillar Inc. “[G399specsheet.pdf (swiftequipment.com)](https://swiftequipment.com/Images/Engines/102233/G399specsheet.pdf)”

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