Vibration Analysis of a Piping System Attached With Pumps and Subjected to Resonance.

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Abstract—Objective of this study is to perform a design analysis for an excessive vibration problem of a piping structure due to mechanically induced resonance. But in most process piping design activities the dynamic vibration analysis of the piping system are not of much interest compared to static analysis. However if process plants come across such problem during their operation then they need to be addressed as critical and should be analyzed in detail. These vibrations are basically induced by the rotating or reciprocating equipment like compressor, pump, turbo machine etc. attached to the piping system. They can be easily detected & monitored by modern condition monitoring facilities. However for rectification, detailed review of piping design for both static and dynamic aspects are absolutely necessary.

Modern computerized design and analysis tools are very much helpful in these cases. In this paper the approach involves both practical evaluation and computer simulation. The practical vibration analysis is done with analyzing actual vibration reading of the piping structure and plotting the operating deflection shape (ODS) using the ME’scope VES™ software. Computer simulation is done for static design review and modal analysis to evaluate natural frequency and mode shapes using piping stress analysis software CAESAR II. This activity also involves the finite element analysis (FEA) technique. Results are compared to verify the cause of resonance and also to find the solution on resonance problem.

Keywords—Mechanically induced resonance, Modal analysis, Mode shape, Natural frequency, piping stress analysis

I. INTRODUCTION

Computer aided design and analysis tools are very useful in the modern days design in every engineering field. Manual calculation is almost impossible task in the advent of techniques like finite element methods to analyze a modern engineering task. The problem of study here is of vibration & stress analysis associated with the process piping design. Vibration analysis with condition monitoring tools and techniques are compulsory in modern refineries for maintenance of plant and machineries. Vibration analysis in piping design is done using computerized tools like experimental ODS analysis and piping stress analysis.

II. LITERATURE REVIEW

Jaroslav Mackerle [1, 2] carried out a bibliographic review and provided a list of papers in FEA of pressure vessels and piping domain. This is during the period 1998 to 2004. These papers provide an over sight to problems in the work area and approaches used. Papers are categorized based on type of analysis done like structural, thermal, fluid etc. His studies were on the pressure vessels which were subjected to static and dynamic analysis using the finite element techniques. The various types of analysis which were conducted included deformation and stress, linear elastic static and dynamic analysis both in 2D and 3D, seismic response analysis and impact analysis. He also performed finite element analysis on the components of the pressure vessel and piping to evaluate the residual stresses, response to detonation loading, damping characteristics, local mechanical behavior studies determining plastic and limit loads, stiffness evaluation and stress concentration factors.

An organized approach to piping vibration assessment and control was provided by Naren Sukaih [3]. Emphasis was on vibration control through measuring and refining the supporting systems. To demonstrate the use and flexibility of the above method a case study was considered, by carrying out a comprehensive stress analysis using CEASAR II software.

Maki M. Onari and Paul A. Boyadjis [4] discussed vibration issues associated with pumps used in chemical plants, refineries and waste water treatment plant. Normally problems associated with 1X and 2X running speed problems due to imbalance and misalignment problems were handled successfully without much difficulty. But vibration due to resonance of structural natural frequency or geometrical changes is complicated. So these type of problems can be handled by ODS analysis and FEA.

Mark H. Richardson and others [5, 6, 7] explained basics of ODS analysis and techniques using ME’scope VES™ software by Vibrant Technology, Inc. USA. Detailed procedures were provided for vibration measurement, modeling and analysis. Various techniques of time domain...
and frequency domain ODS analysis were discussed in detail. Comparison between mode shape and Operating

Deflection Shapes were also provided.

FEA analysis in piping system with gasketed flanged joints at various temperatures was conducted by Mathan and N. Siva Prasad [8]. ANSYS software was used for finite element simulation with thermo-mechanical analysis, which was followed by harmonic and modal analysis. Discussion was done on the important parameters affecting the vibration. Thermal stresses were induced by the temperature of internal fluid which influences the natural frequencies significantly. When a comparison was made between metal gasket and spiral wound gasket (SWG), it was observed that the natural frequencies corresponding to particular modes were influenced by the type of gasket used. A variation of 12.3% in natural frequency occurred for first bending mode shape on behalf of joint with graphite filled SWG compared to metal gasket. The difference in the natural frequencies is more for the particular mode shapes involving deformation of the gasket.

There are various methods to tackle the excessive vibration or resonance in the piping work. Different cases require different methodology, due variation in support configurations, geometrical and structural changes, type of fluid etc. For flow related resonance computational fluid dynamics (CFD) tools can be used. General static and dynamic analysis can be done using CAESAR II. For extensive structural, modal and thermal analysis can be done using ANSYS for few elements of the piping. ODS analysis can be done for modal as well as stress analysis with real time vibration measurement systems.

III. PROBLEM DEFINITION

Vibration in one of the piping was identified in Mangalore Refinery and Petrochemicals Limited (MRPL), Mangalore. The piping was attached with vacuum residue pumps tagged as GA31106 A and B at Phase III plant. As per initial observations from condition monitoring system high vibrations were found in pump side. There was also some visual vibration present in the discharge line. Reason for this vibration was investigated by analyzing the vibration pattern suitable for a period time. From the vibration pattern as shown in figure 1, it was clear that 1X horizontal velocities were around 16.07 mm/s, which was higher than the permitted limits as per ISO 2372(7.1 mm/s). Vertical and axial velocity readings were around 5.85 mm/s, which was within the limit as shown in figure 2. In the motor side the velocity readings were around 1.6 mm/s which were within the limit of 7.1 mm/s. All these indicated clearly that there was no rotor imbalance problem. When pump B was analyzed, same vibration patterns were observed, justifying the cause of excessive vibration as resonance in discharge piping. Thus through condition monitoring technique the resonance in piping was detected. The objective of the present investigation was to find the resonance and rectify this excessive vibration problem. ODS analysis and piping stress analysis were considered for the solution in this case.

![3D plot of Horizontal Vibration pattern from 21-09-2012 to 14-11-2013 for Pump GA31106A](image3)

![3D plot of Vertical vibration pattern from 21-09-2012 to 14-11-2013 for Pump GA31106B](image4)

IV. THEORETICAL BACKGROUND

4.1 Operation deflection Shape (ODS) Analysis.

ODS analysis is done to obtain the operating deflection shape or Mode shape and natural frequency. For representing the forced linear vibration in time domain of an elastic structure we use the expression, 

\[ [M] \ddot{x}(t) + [C] \dot{x}(t) + [K] x(t) = f(t) \]  

This equation is from Newton’s Second Law. A force balance is obtained among the three types of internal forces in any structure made out of elastic materials. These internal forces are the inertial (mass), dissipative (damping), and restoring (stiffness) forces. Inertial and restoring forces are sufficient to cause resonant vibration. However, some form of damping is always present in all real structures, if none other than the viscous damping caused by displacement of the air surrounding the vibrating structure.

Solution to above equation gives the Operating Deflection Shape (ODS). Therefore the above time domain responses are converted in to frequency domain responses using Fast Fourier Transforms (FFT). So an equivalent frequency domain form of the dynamic model for a structure can be represented in terms of Fourier transforms as,
\[ X(j\omega) = [H(j\omega)] \{F(j\omega)\} \quad \cdots \cdots \cdots \quad (2) \]

The ODS can now be defined as a solution to above equation. There are two types of solutions, namely time domain and frequency domain solution. The frequency domain ODS is defined as the forced response at a specific frequency \( (j\omega) \),

\[ \{\text{ODS}(j\omega)\} = \{H(j\omega)\} \{F(j\omega_0)\} \quad \cdots \cdots \cdots \quad (3) \]

This equation says that the ODS is prepared by summation of vectors, each one identical to the Fourier transform of an excitation force times the column of FRFs agreeing to the excitation. From this it is clear that the ODS is reliant on the applied external forces.

By taking the inverse FFT (FFT\(^{-1}\)) of both sides of equation the time domain ODS is generated as,

\[ \{\text{ODS}(t)\} = \text{FFT}^{-1}\{H(j\omega)\} \{F(j\omega)\} \quad \cdots \cdots \cdots \quad (4) \]

4.2 Static and Dynamic analysis for Piping Vibration

In the case of piping work vibration attached to rotating equipment, the static and dynamic analysis is a must to evaluate natural frequency, damping and mode shape. So by altering the natural frequency or damping we can reduce the excessive vibration or resonance. Natural frequency of piping can be varied by appropriate pipe span length and support configuration. Damping is altered by material damping (plasticity) and structural damping (friction) variations.

Hence better support configuration and pipe span length can be determined by static analysis. Natural frequency and mode shape can be evaluated by dynamic analysis.

4.2.1 Support Configuration and Natural frequency of piping system.

Natural frequency of piping span with two simple supports are given by the equation as below

\[ f_o = \frac{\lambda}{2\pi} \sqrt{\frac{gE}{\mu L^4}} \quad \cdots \cdots \cdots \quad (5) \]

This formula is applicable only for simply supported beam, so the natural frequency for complex piping systems can be evaluated by computer programs using finite element analysis (FEA) techniques like in CAESAR II software.

V METHODOLOGY

The entire methodology to solve excessive vibration in the piping structure is as shown in figure 3. The method is divided into two parts, namely experimental ODS analysis and design review using piping stress analysis software with FEA techniques. Results from the experimental ODS analysis mainly provides the response frequencies in the piping system and the relative movement of the nodes by plotting the Operating Deflection Shape. This provides the segment of the piping work that needs to be analysed in detail for support configuration, natural frequency etc. In the second part a design review is carried with vibration and stress analysis. The entire piping system is modelled in the piping stress analysis software for both static and dynamic analysis.

Static analysis provides the information about support configurations, stress distribution and response displacement along various node points. Dynamic analysis provides natural frequency of piping system with mode shapes. Finally both experiential ODS analysis results and results from design review using piping stress analysis software are compared. Based on this comparison necessary design changes are suggested to find the solution for mechanically induced resonance.

5.1 Experimental ODS analysis.

In the experimental method, operating deflection shape at desired frequency can be plotted using measured vibration data and analysing the same in ME’scope VEST™ software. Hardware tools used are

a) Data acquisition device and transducer (SKF make Microlog analyzer CMVA60 and accelerometer with range 0.5Hz to 20Kz)
b) External Trigger Device (Optical stroboscope kit)
c) Interface cable (to connect external trigger (Optical stroboscope) and the analyzer facilitating signal transfer)

Piping is modeled in software with various node points as shown in figure 4, where vibration measurements need to be taken. An inspection route was created in the software and downloaded to equipment used for real time vibration measurement. The vibration data is then again uploaded to the ODS software as shown in figure 5. Analysis was done for response frequencies and operating deflection shape.
A list of harmonic resonant frequencies was generated from ODS analysis and is as shown in Table 1. Magnitudes and phases of displacement shapes for each resonant frequency were also generated. It was clear from these tables that the resonance is dominant at operating frequency (49.9 Hz). Line with nodes 32, 33, 34 and 35 are showing the resonance with operating frequency and shows horizontal vibrations as indicated in Figure 6.

![Image](image1.png)

**Figure 3:** Flow chart for methodology

![Image](image2.png)

**Figure 4:** Piping system modeling in ME’scope VES™ Software by vibrant technology Inc. U.S.A.

![Image](image3.png)

**Figure 5:** Enlarged view of last vibration Data block uploaded to ODS software from the Microlog.

![Image](image4.png)

**Figure 6:** Operating deflection shape at resonance Frequency (49.9 Hz) position 3

<table>
<thead>
<tr>
<th>Shape</th>
<th>Label</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31106new</td>
<td>49.88648</td>
</tr>
<tr>
<td>2</td>
<td>31106new</td>
<td>99.77296</td>
</tr>
<tr>
<td>3</td>
<td>31106new</td>
<td>149.6595</td>
</tr>
<tr>
<td>4</td>
<td>31106new</td>
<td>199.5459</td>
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<td>31106new</td>
<td>249.4324</td>
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<tr>
<td>10</td>
<td>31106new</td>
<td>498.8648</td>
</tr>
</tbody>
</table>

### Table 1: List of response frequencies (Hz) from ODS analysis

**5.2 Design review in piping stress analysis software CAESAR II**

Design review on the piping structure modelled in CAESAR II was conducted with static and dynamic analysis with basic inputs as per code ASME B31.3. In dynamic module modal analysis and harmonic analysis was carried out.

- Operating pressure: 140 KPa
- Operating temperature: 60°C
- Hydro test pressure: 210 KPa
- Material of construction: A 106 Grade B pipe with corrosion allowance 3 mm

#### 5.2.1 Piping System Modeling and Analysis

Piping system is modeled by using PMS (project material specification), PID (process and Instrumentation diagram) and Isometric drawing of the piping work concerned. In the software, modeling is done by using various piping elements like pipe, bend, flange, reducer, valve, tee etc. as shown in figures 7. Displacement boundary conditions were provided through various support or restraint like anchor, guide, spring hangers and stops as shown in figure 8. This work falls in ASME B 31.3 process piping category. Design code provides material grade, properties and dimension details for each element of the piping model.
5.3 Results and conclusions

- Static analysis results were acceptable as per CODE ASME B31.3, so design is safe for static aspects.
- In modal analysis, natural frequencies were listed as shown table 2. This clearly indicates natural frequency is matching with operating frequency of 50 Hz justifying the mechanically induced resonance. Mode shape at frequency at 49 Hz is as shown in figure 9.
- In harmonic analysis the deflection shape at forcing frequency equal to operating frequency of 50 Hz matching with mode shape justifying the resonance.

**TABLE 2: Natural frequency list from modal analysis in CAESAR – II**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106.674</td>
</tr>
<tr>
<td>2</td>
<td>111.212</td>
</tr>
<tr>
<td>3</td>
<td>125.495</td>
</tr>
</tbody>
</table>

VI. METHODS TO AVOID RESONANCE

After comparison of results from experimental ODS analysis and design review in CAESAR II mechanically induced resonance was justified. To achieve the main objective of solving mechanically induced resonance in the piping system, below approaches can be utilized.

- By vibration Isolation
- By damping the vibration
- By modifying natural frequency of the piping system

Modification of natural frequency is considered here since this is comparatively easier and with lower cost implications as operating frequency is fixed. This can be achieved by varying the support configuration of the piping system which in turn varies the stiffness and natural frequency of the piping system. We can change natural frequency either higher or lower. Keeping natural frequency higher results in stiff piping and also results in better design considering fatigue aspects of piping system. From the literature [9], natural frequency vs pipe span table, the total length of the piping work (6.625 inch outer dia.) from node 310 to 320 is 5300mm. This is around 17.6ft. From the table, to shift natural frequency to around 100Hz (2 X RPM) the length required is around 7 feet for an outside diameter of 6.625inch. So one more support is needed between node 310 and 320 to shift the natural frequency to 100 Hz. Hence an extra support at node 315 is introduced. Static and Modal analysis is carried out to verify the effect of change.

**TABLE 3: Natural frequency list from modal analysis in CAESAR-II for modified piping system**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.012</td>
</tr>
<tr>
<td>2</td>
<td>52.3010</td>
</tr>
<tr>
<td>3</td>
<td>56.4374</td>
</tr>
</tbody>
</table>
VII. CONCLUSIONS

- The ODS analysis was performed in ME’scope VEST™ software provides the operating deflection shape at the desired frequency of 50 Hz.
- The design review (static and dynamic analysis) for piping system was carried out in piping stress analysis software CAESAR II. Static results were acceptable.
- The axial, horizontal & vertical loads and associated moments were listed for each node for all the load cases. Acceptable upper limit for load value is 4000 kg.
- Maximum stress developed in all the elements and nodes are listed for specified load case. The maximum code stress ratio is 82.6 at node 740 on the pump discharge line. Acceptable range for code stress ratio is 0% to 100%.
- Displacements at all nodes for each load case are listed. This can be verified with specified code limits of 10 mm maximum at any node. Thus design is safe as per static analysis.
- The modal analysis was performed in dynamic analysis module of CAESAR II and natural frequency was nearly equal to operating frequency and thereby causing mechanically induced resonance. Modes shapes are almost matching with operating deflection shape at 50 Hz.
- Modification of the support configuration was implemented in CAESAR II model of piping work.
- The modal analysis of the same clearly indicates the shift of the natural frequency of the piping system away from operating frequency (50 Hz) and there by becomes the solution for resonance problem.

NOMENCLATURE

- [M] Mass matrix (n X n order, force/unit acceleration)
- {i (t)} Velocity response vector
- [K] Stiffness matrix (n X n order, force/unit displacement)
- {x (t)} Displacement response vector
- {f(t)} Excitation force vector
- [H (j ω)] Frequency Response Function (FRF) matrix
- {X (j ω)} Displacement responses vector of discrete Fourier Transforms
- {F (j ω)} External forces vector of discrete Fourier transforms.
- g Gravitational constant 9.86 m/sec²
- E Modulus of elasticity KPa
- I Moment of inertia mm⁴
- μ pipe Weight per unit length kg/m
- λ frequency factor dimensionless(depending on mode)

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References