High Energy Vibration for Gas Piping

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Abstract. In September 2016, a gas compressor in offshore Sarawak has its rotor changed out. Prior to this change-out, pipe vibration study was carried-out by the project team to evaluate any potential high energy pipe vibration problems at the compressor’s existing relief valve downstream pipes due to process condition changes after rotor change out.

This paper covers high frequency acoustic excitation (HFAE) vibration also known as acoustic induced vibration (AIV) study and discusses detailed methodologies as a companion to the Energy Institute Guidelines for the avoidance of vibration induced fatigue failure, which is a common industry practice to assess and mitigate for AIV induced fatigue failure. Such detailed theoretical studies can help to minimize or totally avoid physical pipe modification, leading to reduce offshore plant shutdown days to plant shutdowns only being required to accommodate gas compressor upgrades, reducing cost without compromising process safety.

Keywords: Acoustic-induced vibration; AIV; high-frequency acoustic excitation; HFAE; high-energy vibration

1. Introduction

Vibration induced fatigue failure of pipework is an area of concern in the oil & gas industry due to negative impact towards process safety, production down time, cost and environmental impact. Acoustic induced vibration (AIV) is a type of vibration induced fatigue failure caused by high pressure drop devices in a gas system such as pressure relief valve, blowdown valve, orifice restriction plates and control valves which can generate high sound power levels in the pipework.
The time to failure from AIV is short (typically a few minutes to hours) due to high frequency response and high tonal noise levels external to the pipe, forming a high frequency vibration which are commonly between 500 to 2000Hz [1].

The AIV phenomenon was first reported by Carucci and Mueller in 1982. Curucci and Mueller showed the relationship between pressure drop and pipe diameter based on actual 36 cases where high vibrational levels had resulted in either pipe failure, non-failure or no abnormal experience [2]. In 1997, Eisinger further explored relationship between pipe diameter and pipe wall thickness (D/t) and the expected sound power level at which failure could occur [3]. The Energy Institute (EI) published a document known as “Guidelines for Vibration Induced Failure in Process Pipework” in 2008. The EI guidelines introduced empirical formula to calculate the Likelihood of Failure (LOF) at each pipe discontinuity (e.g. branch fittings, tee joints). If the LOF score = 1, the design changes / physical modification is mandatory which include one or more of the following mitigation measures to improve the LOF score:

a. Eliminating stress concentrations (e.g. removing pipe discontinuity)
b. Increasing pipe wall thickness, to reduce stress concentration at the pipe wall discontinuity.
c. Use of contoured fittings such as forged tees or sweeplets instead of wellolet fittings to reduce stress concentration at the pipe wall discontinuity.
d. Reduce mass flow rates
e. Use of low noise valve trims (applicable only for control valves)
f. Full wrap around reinforcement to reduce stress concentration at the pipe wall discontinuity. Case-by case basis evaluation, which requires finite element analysis to quantify the effectiveness of the reinforcement design.

However, in today’s low-oil price environment, such physical modification is best kept minimal especially for operating plants due to production revenue loss (viz., plant shutdown) to accommodate for the safe site execution.

This paper presents a detailed theoretical methodology to AIV study – via dynamic stress analysis and finite element analysis (FEA) to determine the pipe fatigue life (time to failure), should the EI guidelines LOF calculation method demand a major re-design of the existing pipework.

2. Methodology & Result

2.1 AIV Screening

There are 3 units of relief valves (RV-102, RV-103, RV-104) at the compressor discharge line. Similar to EI Guidelines, process data for each relief valve was obtained (Table 1) to calculate the sound power level (PWL) generated by each relief device for AIV screening as shown in the equation [1] below:

\[
PWL = 10 \log_{10} \left( \left( \frac{P_1 - P_2}{P_1} \right)^{3.6} W^2 \left( \frac{T}{Mw} \right)^{1.2} \right) + 116.2 + SFF \tag{1}
\]

Where:
- \(P_1\) = is upstream pressure (bara)
- \(P_2\) = is downstream pressure (bara)
- \(W\) = is flowrate (kg/s)
- \(T\) = is upstream temperature (K)
- \(Mw\) = is molecular weight (grams / mol)
\( SFF = \) is a correction factor to account for sonic flow. If sonic conditions exist then \( SFF = 6; \) otherwise \( SFF = 0 \)

If the calculated PWL exceeds 155dB, then the screening fails.

**Table 1:** Process parameters for AIV screening

| Device | Set pressure (barg) | P1, inlet pressure (bara) | Mass flow rate (kg/hr)\(^a\) | Inlet temp (K) | P2,back-pressure (bara) | Molecular weight (g/mol) | Sound power Level (dB) |
|--------|---------------------|---------------------------|-------------------------------|----------------|--------------------------|--------------------------|-----------------------|
| RV-102 | 110                 | 118.6                     | 218444                        | 359.6          | 13.7                     | 19.08                    | 174.39                |
| RV-103 | 113                 | 118.2                     | 118819                        | 359.5          | 9.6                      | 19.08                    | 168.38                |
| RV-104 | 115                 | 118.9                     | 80795                         | 359.7          | 10.5                     | 19.08                    | 165.12                |

\(^a\) Mass flow rate from each relief valve is different due to staggered opening (viz., set pressures are set differently for each device) of the relief valve during overpressure scenario.

All 3 relief valves have failed the AIV screening, with PWL exceeding 155dB. The recommendation by EI guidelines is to perform further AIV analysis to determine the LOF at each discontinuity. The next section will discuss on the result using the dynamic stress analysis method as a detailed assessment.

### 2.2 Dynamic stress analysis method

For this further analysis via dynamic stress analysis method, each discontinuity at the downstream of the relief valve downstream pipe is identified in-terms of connection type (viz., weldolet, tee joint), material type and branch diameter size. The sound power level is then translated to pipe wall vibration so as to obtain the dynamic stress \( \sigma_{\text{dyn}} \) generated [4, 5].

The dynamic stress is then compared against ASME VIII Div. 2 fatigue curve limits [6] to calculate the pipe discontinuity fatigue life. These limits determined based on the device operating duration and pipe discontinuity material type.

An instrument protective function study was carried out to determine the relief valve operating duration. This involves checking the robustness of the available safeguarding system of the compressor in an overpressure scenario, before having to activate the relief valves (*Relief devices are generally the last line of defence for overpressure events*). From the study outcome, the relief valve demand was determined to be once in 20 years, which is well within of a typical plant design life of 20 years. Such event is classified as short & rare event and the accepted dynamic stress limits are as follows:

**Table 2:** Dynamic stress allowable limits for short & rare operating duration.

| Operating duration | Carbon steel | Austenitic Stainless Steel |
|--------------------|--------------|---------------------------|
| Short & rare event | \( \sigma_{\text{dyn}} < 105\text{MPa} \) | \( \sigma_{\text{dyn}} < 148\text{MPa} \) |
A result comparison of EI LOF calculation method vs dynamic stress method is shown in table 3. The dynamic stress method now enabled us to focus on only one failure case (viz., Configuration A) instead of all the four failure cases (viz., Configuration A to D).

**Table 3:** AIV result comparison between energy institute guideline vs. dynamic stress method

| Configuration | Discontinuity (Branch Diameter Size (mm) x Connection type) | Main Pipe Outside diameter (mm) | Pipe wall thickness (mm) | Pipe Material | Energy Institute LOF | Pipe Redesign Mandatory? (Mandatory / Recommended / Not mandatory) | Dynamic Stress Levels (MPa) | AIV analysis (Pass / Fail) |
|---------------|-------------------------------------------------------------|---------------------------------|--------------------------|---------------|-----------------------|-------------------------------------------------------------|-----------------------------|--------------------------|
| A             | DN20 weldolet                                               | 323.8                           | 14.27                    | Carbon Steel  | 1.00                  | Mandatory                                                   | 125                         | Fail                     |
| B             | DN300 tee                                                   | 406.4                           | 9.53                     | Austenitic Stainless Steel | 0.77               | Recommended                                                 | 127                         | Pass                     |
| C             | DN50 weldolet                                               | 406.4                           | 9.53                     | Austenitic Stainless Steel | 1.00               | Mandatory                                                   | 127                         | Pass                     |
| D             | DN80 weldolet                                               | 406.4                           | 9.53                     | Austenitic Stainless Steel | 0.94               | Recommended                                                 | 110                         | Pass                     |

The main difference in results between EI and dynamic stress methods is due to fatigue life evaluation. The EI method uses fatigue life curves in accordance with BS 7608 or PD5500 while the dynamic stress method uses ASME Div. II fatigue life curves. BS 7608 or PD5500 provides comprehensive fatigue life for weld classes, whereas EI penalizes for using fillet weld type such as weldolet connections. As opposed to EI Guidelines, the dynamic stress method was developed based on ASME Div. II [6] has comprehensive fatigue life curves for different materials such as carbon steel and SS300 series high-alloy steel.

Furthermore, while LOF=1.0 at the discontinuities in EI Guidelines mandates redesign, corrective actions and/or detailed analysis of AIV, for a LOF less than 1.0, EI provides vague guidance which only covers recommendations (i.e. optional) for further analysis [1] (table 4). An LOF below 0.5 is considered as a pass for AIV analysis. With dynamic stress analysis method, the AIV analysis provides better quantitative approach, where AIV result is a pass or fail based on the material and duration of the operating device (viz. sound power source).
Table 4: LOF interpretation as per EI guidelines [1]

| Score          | Action                                                                                                                                 |
|----------------|---------------------------------------------------------------------------------------------------------------------------------------|
| LOF $\geq 1.0$ | The main line shall be redesigned, resupported or a detailed analysis of the main line shall be conducted, and vibration monitoring of the main line shall be undertaken (*Note 1*) Corrective actions shall be examined and applied as necessary Small bore connections on the main line shall be assessed. A visual survey shall be undertaken to check for poor construction and/or geometry and/or support transmission to neighbouring pipework. |
| $1.0 > \text{LOF} \geq 0.5$ | The main line should be redesigned, resupported or a detailed analysis of the main line should be conducted, or vibration monitoring of the main line should be undertaken (*Note 1*) Correction actions should be examined and applied as necessary Small bore connections on the main line shall be assessed. A visual survey shall be undertaken to check for poor construction and/or geometry and/or support transmission to neighbouring pipework. |

2.3 Finite Element Analysis Method
Since the discontinuity at DN20 weldolet (Configuration A) failed in the dynamic stress analysis study, a more advanced AIV study via finite element analysis (FEA) was utilized to further optimize the accuracy of the dynamic stress calculation. FEA was used to simulate the piping vibration excited by pipe internal sound dynamic pressure and calculate the piping dynamic stress resulting from the vibration.

Additional information such as the actual discontinuity geometry and site visual condition was taken into FEA to model the discontinuity accurately and reflect the as-built conditions of piping. FEA modelling was done using Nastran FEMAP (version 11.2) software. The drain connection was modelled using solid elements for detailed stress prediction; Plate elements were used for other areas of the model (i.e. to simulate constraints and for accurate mode shape prediction); The boundary conditions are shown in the screenshot of the model in figure 1.

The calculated dynamic stress from FEA modelling was calculated to be 66.1MPa (figure 2) which passed the AIV analysis as the dynamic stress is less than 105MPa.
Figure 1: FEA modelling of DN20 x weldolet discontinuity

Figure 2: FEA model showing the location of maximum dynamic stress at the pipe discontinuity.
3. Conclusion

The compressor relief line has undergone an AIV study which comprise of (1) AIV screening using the EI method, (2) intermediate study was conducted using 2 methods which are EI guidelines and dynamic stress analysis method and (3) advance study was done using the FEA method. The discontinuity at the relief lines were found to be of no AIV concern and no physical line modification is required to mitigate AIV issues.

In addition to the EI Guidelines, the dynamic stress analysis provided a more refined fatigue estimation and the FEA method was able to fine tune the stress values to optimize the pipe’s fatigue life which can be used to evaluate the AIV risk of existing process pipe. Through calculation of pipe fatigue life, this can help plant operators to better quantify the AIV risk to decide the extent of the required site physical modifications to mitigate AIV issues. In this case, it helped to avoid pipe modification at site. Such avoidance of physical pipe modification minimised shut-down/turn-around time required, plant production loss and site HSSE risk exposure, so it helped complete the project safer, faster and cheaper.

References

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