Use of composite wraps to prevent acoustic induced fatigue failure in piping systems

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Abstract

In gas piping systems, during a pressure let down through pressure safety valves, the downstream piping may be susceptible to acoustic induced fatigue failure. This is a situation that poses financial risks to the company as well as environmental and health and safety consequences. The current methods for mitigating these risks are complex, expensive and/or require long shut downs to execute. The objective of this project is to determine the usability of composite overlays as a means for improving the reliability of pipelines which experience large amounts internal sound power and vibration. This research focuses on modelling the excitation of a pipe in simple conditions and experimentally verifying the extent to which the composite wraps reduce the vibroacoustic response of the pipe as well as the pipe stress. The materials science aspects of the project (which includes finite element analysis) are the subject of separate research.

1. Introduction

In LNG process plant operations, there is interest surrounding the integrity of piping when exposed to acoustic induced vibrations. In the case of a pressure letdown, a great deal of noise can be created at the pressure safety valves (PSV). This noise has the propensity to cause resonant vibrations in the pipework, which can lead to fatigue failure of the component.

The implications of such an event include financial, environmental and health and safety issues. In the case where an existing pipe is identified as susceptible to acoustic-induced vibration (AIV), there a number of remedial strategies which can be undertaken but are all either logistically difficult or expensive solutions to the problem, and all require lengthy shutdowns. These include, but are not limited to:

- Modifying the process system
    - Splitting the total inventory of the stream to reduce the pressure.
    - Multi-stage pressure let down
- Redesigning the piping system
    - Completely replace component with one which is designed to reduce the generation of AIV.
    - Re-design the flare/discharge header to be resistant to AIV. This would involve re-routing some or all of the PSV discharge piping and connecting to a point on the header sufficiently downstream of potential stress concentration points.
    - Remove local stress concentrations (fillet welded pipe supports and small bore

fittings) and install local stiffening rings to increase the natural frequency of the pipe.
- Increase pipe wall thickness.

The primary objective of this research is to provide conclusive evidence relating to the feasibility of the use of composite wraps as a means for mitigating acoustic induced vibration in pipes.

1.1 Background Information

It is common practise for the gas processing industry to evaluate the level of risk of AIV in piping systems. Figure 1 provides an example of the analysis of a section of piping based on one possible set of guidelines.

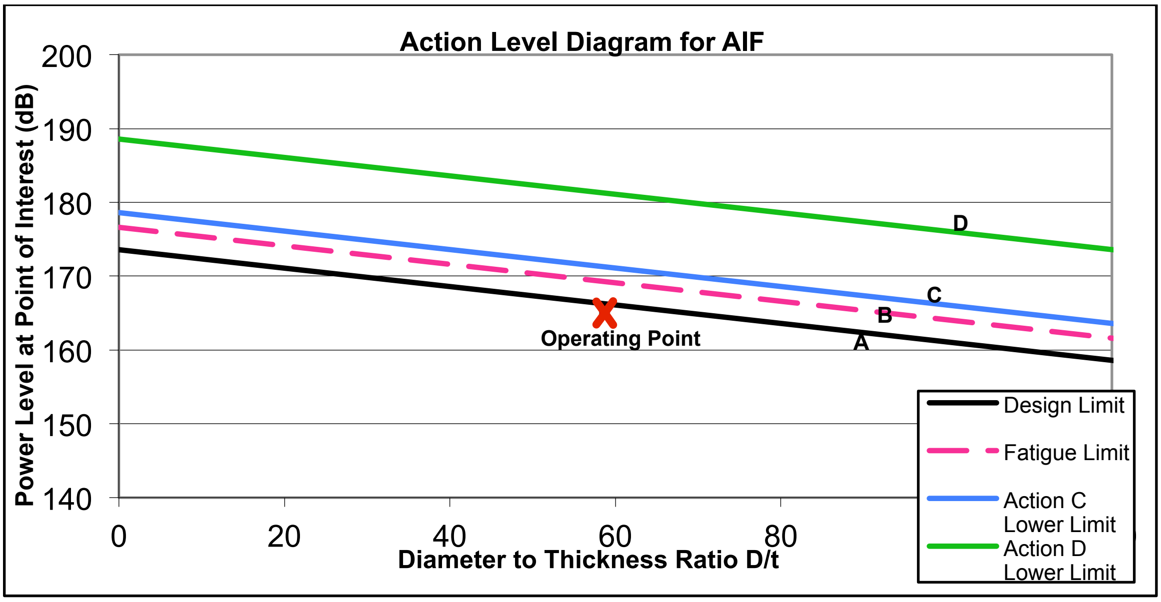

Figure 1 Analysis shows the sound power level in the sample pipe falls within the design limit proposed in this example guideline

The initial research supporting the example guidelines in Figure 1 is taken from the ASME paper "Acoustically Induced Vibration in High Capacity Pressure Reducing Systems" by Carucci and Mueller and additions by Eisinger (Eisinger, 1997) and gives an insight into the mechanics behind acoustic fatigue and provides a method for risk analysis. Although guidelines based on these papers provide general recommendations to prevent acoustic fatigue in newly designed pipes, there is little guidance as to how to prevent fatigue in an existing piping system. No publically-available research has been conducted in to the viability of composite wraps as a remedial technology.

2. Methodology and Modelling

There are number of phases that need to be carried out in order to produce meaningful and conclusive results. Intially, it was important to develop an understanding of the current state of the art in this field. This was achieved by reviewing relevent literature. The literature review is ongoing throughout the project, but an initial analysis was critical in defining the scope and direction of the research.

The primary initial focus was on gaining an understanding of the way in which pipes vibrate, especially when excited by a disturbance of internal flow. In particular, in determining how a given pressure drop and fluid velocity will induce vibration in the pipe and what stresses the pipe wall will experience in this situation. There is a great deal of literature that addresses the propogation of sound through a pipe wall but surprisingly little work has been done in analysing sound propogation along the axial direction of the pipe. Mason's work on the propogation of sound along a cylindrical duct contains the theory necessary for predicting the sound power at different points in a pipe section given the sound power at the source. The theory presented is for "if the fluid in the tube is moving with constant velocity v" and yields the equation of acoustic pressure as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left\{r\frac{\partial p}{\partial r}\right\}+\frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2}+\frac{\partial^2 p}{\partial z^2}=\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}+\frac{2M}{c}\frac{\partial^2 p}{\partial z \partial t}+M^2\frac{\partial^2 p}{\partial z^2}$$

where v = fluid velocity; c = speed of sound in the medium; p = pressure; r, θ, t = cylindrical polar coordinates; and $M = v/c$ (Mason, 1969). This theory is crucial in determining the sound power present in vulnerable areas.

More importantly, the literature review focused on the vibroacoustic response of a pipe to a given pressure drop and the pipe stress induced by this. The most conclusive and reliable source that has been studied is Karczub's PhD thesis (Karczub, 1996). The work looks at three different practical methods of determining pipe stress. However, the theory contained in the early chapters can be used to predict the stress. "Using the separated wave components, the complete travelling wave solution may be expressed as

$$u(x,\theta,\omega)=\sum_{n=0}^{\infty}\sum_{s=1}^{8}U_{ns}\cos(n\theta)\,e^{k_{ns}x}e^{i\omega t}$$

$$v(x,\theta,\omega)=\sum_{n=0}^{\infty}\sum_{s=1}^{8}V_{ns}\sin(n\theta)\,e^{k_{ns}x}e^{i\omega t}$$

$$w(x,\theta,\omega)=\sum_{n=0}^{\infty}\sum_{s=1}^{8}W_{ns}\cos\,(n\theta)e^{k_{ns}x}e^{i\omega t}$$

where U_{ns}, V_{ns} and W_{ns} are the complex wave amplitudes for circumferential mode n and axial wave s, and $\omega = 2\pi f$ is the angular frequency" (Karczub, 1996). The path to predicting the stress is then extracting the characteristic equation at a non-dimensional frequency. This is done by substituting the travelling wave into the equations of motion. The result is a 3x3 homogenous matrix equation with unknowns U_{ns}, V_{ns} and W_{ns}. We then equate the determinant of the coefficient matrix to zero for non-vanishing U_{ns}, V_{ns} and W_{ns} (Karczub, 1996).

The theory contained in this piece of literature can be paired with work by Sorokin and Terentiev to yield a model that maps a pressure drop to theoretical pipe stress. The article maps a pressure drop to the vibroacoustic response of the pipe using the following equation:

$$\frac{\delta^2 p_m}{\delta x^2}+\frac{\delta^2 p_m}{\delta r^2}+\frac{1}{r}\frac{\delta p_m}{\delta r}-\frac{m^2}{r^2}p_m+\frac{\omega^2}{c^2}p_m=-\rho_{fl}\Gamma^{(m)}(x,r)$$

where "the acoustic excitation is specified as $\Gamma^{(m)}(x,r)$" and represents a large second order partial differential expansion. The shell vibration can then be solved for and "is described in the framework of Goldenvejzer-Novozhilov thin shell theory (Sorokin & Terentiev, 2006)."

After gaining an understanding of how pipes vibrate and the different ways one can model this, a mathematical model can be developed to study acoustic induced vibration. The model will be built in Matlab and will serve to provide a theoretical basis for the experimental stage of the research project. At this stage it will be important to simulate vibrations caused by a pressure drop similar to one that would be experienced by a pipe on site.

With the information gathered during the initial stages, an experiment has been designed to provide evidence to support or reject the theoretical claims. The experiment will involve exciting the pipe using either a loudspeaker or compressed air and measuring the response of the pipe at different locations. The experiment will allow the student to assess the effects that different wraps have on the vibrations of a pipe. This experiment is designed to model the AIV caused by the internal pressure drop typically experienced in a pressure let down.

4. Experimental Setup

The experimental phase of the research has been constructed to allow simple analysis of the system. There are a number of important factors that had to be considered when designing the rig:

- The readings should be strong enough to ensure that ambient noise plays a negligible role in influencing the results
- The rig should be designed in such a manner that it will be possible to test the response of the system to single-frequency excitation
- The rig should also be designed to simulate a situation similar to that of a pressure let down
- Measurements should be taken at a significant distance from the source to allow flow to develop
- The rig should be simply supported to conform with the assumptions made in the theory collected in the literature review
- The system should be set up to measure the sound power, the vibrational velocity of the pipe and the stress fluctuations in the pipe.
    - Measurements of sound should be conducted both inside and outside the pipe to allow comparison of testing between bare pipe and wrapped pipe
- Testing should be conducted on a range of sizes of pipes to obtain results for a variety of D/t values. This will allow results to be made applicable to Action Level method of evaluation outlines in section 1.1

With these in mind the following experimental platform was designed and continues to be built. Three pipes are blasted and cut to varying lengths of roughly 3250mm. The pipes are blasted to SAE2.5 roughness and have 75μ surface profile. These values were agreed upon with Furmanite (a local supplier and installer of composite wraps) in order to ensure the success of bonding the wrap to the pipe.

The open pipe ends have been fitted with flanges in order to allow two different plates to be attached. One plate features a compressed air female adaptor to introduce air flow in the pipes. The second has a threaded bore to which a loudspeak can be fastened. Having these two separate excitation methods allows the system to accommodate single-frequency excitation as well as simulate the flow-induced vibrations present in a pressure let-down situation. Both of these excitation methods produce a great deal of noise and ensure that the readings will be strong enough to ensure that ambient noise plays a negligible part in influencing the results.

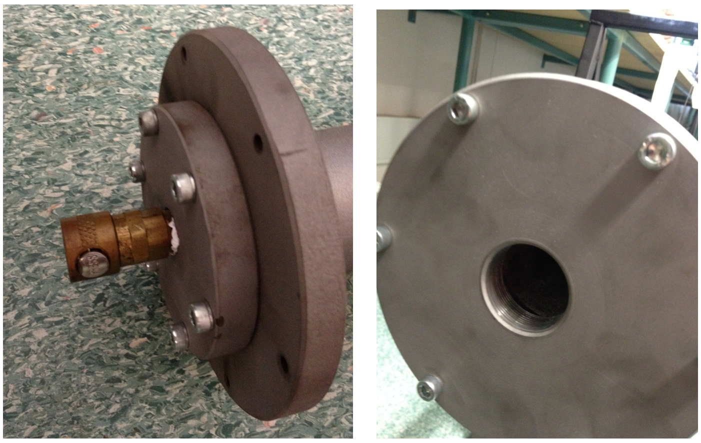

Figure 2 Pipe flanges and respective plates to allow excitation

These pipes are, as required, simply supported by frames that were available in the test lab. Similarly, another stand is used to support an internal probe. The probe allows the student to take sound power readings inside the pipe in order to compare with external readings. It is crucial that the probe remains seperate from the vibrating system, that is the source and pipe, so as to minimise interferance with the readings. In order to achieve this, channel is used to minimise bending deflection to ensure that the probe does not contact the pipe wall.

Figure 3 Diagram illustrating probe design

The sensors are used to measure the response of the pipe in a 1000mm section that begins 1750mm from the source. The distance from the source is left to allow the flow of air to fully develop before reaching the test area. Strain gauges are bonded at each end of the test section and measure the dynamic strain in the pipe wall. Microphones are positioned internally and externally to measure the the power drop across the pipe wall. Microphones are placed at varying locations to minimise the effect that sound nodes have on the results. Similarly, accelerometers will be used to measure the pipe wall vibration. The sensors are connected to their respective amplifiers before being fixed to a central multichannel data acquisition system.

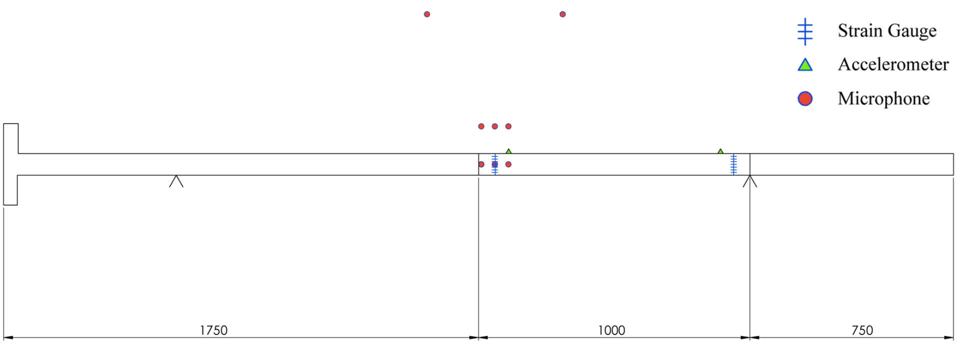

Figure 4 Simplified experimental layout

Measurements will be taken on each bare pipe before wrapping the pipes to compare the results with the system including the composite overlay. Ideally, the composite will be added incrementally to allow readings to be collected for different wrap thicknesses. It is not clear yet whether this will be possible.

The results will be compared to develop a relationship between total sound power, diameter to thickness ratio, and wrap thickness and material. The goal is provide a relationship that gives more clarity to the Action Level model for classifying a pipes risk of experiencing acoustically induced fatigue failure.

5. Future Work

Future work includes further testing and analysis on the bare pipes before wrapping occurs. Wrapping will be outsourced to Furmanite before testing can be conducted on the wrapped pipe. These results will be compared with the results collect in the initial testing phase and conclusions will be drawn as to the effectiveness of composite wraps in reducing the risk of acoustically induced fatigue failure in pipes.

6. References

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