# Gas Piping System Fatigue Life Estimation through Acoustic Induced Vibration (AIV) Analysis

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***Abstract*—In this study, the sound power level of the gas piping system was determined at the sources of vibration and at each discontinuity using the criteria of sound power level limit curves and the Likelihood of Failure (LOF). A detailed finite element model of the connection was developed, and a random acoustic field equivalent to the acoustic power level calculated by generating and applying a pressure field on the walls and summing up the stresses resulting from excitations. This study would help minimise or avoid physical pipe modification, reducing the offshore plant shutdown time while enhancing the safety of the plant. Also, modifications such as alteration in pipe size (diameter and thickness) should be implemented to reduce the Acoustic Induced Vibration (AIV) effects to an acceptable level.**

***Index Terms*—AIV, fatigue failure, gas piping system, FEM, branch connection**

## I. INTRODUCTION

In the gas piping systems of processing facilities, high-velocity hydrocarbon gases frequently pass through restrictions or pressure-reducing devices, such as the Control Valve (CV), Pressure Safety Valves (PSV), or Restriction Orifice (RO). The high differential pressure across these valves tends to generate a high acoustic frequency, with an excitation between 500 Hz and 2000 Hz [1]. In turn, this frequency could lead to the concentrations of stress in the downstream or upstream piping, particularly in areas with an asymmetric circumference such as the branch connections, tees, or welded pipe supports and anchors. The structural stress generated in a piping system by high acoustic pressure via excitation of gas flow is known as Acoustic Induced Vibration (AIV) [2].

In AIV, the cross-wall (high-order) modes of acoustic pulsation could rapidly develop into piping fatigue failure [3], typically in a few minutes to hours. However, the vibration in the pipe wall shows no detectable changes in the piping structure and gas-flow movements. Thus, this fatigue failure has become a major concern for many companies because it is related to the safety of the plant, production downtime, costs for corrective actions, and the environment. Among the causes leading to a catastrophic accident, the piping fatigue due to AIV ranks the second-highest risk, i.e., 21%, which also results in the release of hydrocarbon gases into the atmosphere [4].

It is, therefore, essential that the problems of AIV failures are attended to at the stage of designing the piping systems to minimise or even eliminate any excessive excitations [5]. Although there are many design guidelines available, the oil and gas industry, following the guidelines of the European association for safety, health, and environment (SHE), has adopted the Carucci/Mueller calculation methodology and design curve for most of their AIV screening strategies. Meanwhile, the Energy Institute, UK has been updated based on the Marine Technology Directorate (MTD), UK to provide a procedure and guidelines to countermeasure the acoustic vibration fatigue in pipelines [1].

Also, once the piping systems have been commissioned, it is equally important to measure the vibration levels for predicting the necessary corrective modifications needed for the systems or its support structure. Alternatively, the vibration-contributing excitation mechanisms must be altered or eliminated [5]. Therefore, this study aimed to identify the potential sources of AIV in the gas facility via the estimation of fatigue life due to AIV by determining the likelihood of failure and redesign of pipe mainline at the small-bore connection (SBC).

In predicting the necessary corrective modifications needed for piping failure, empirical design curves are used to calculate the failure probability using the pipe diameter-to-thickness ratio and acoustic power as an input in previous studies, which yielded less accuracy estimate for fatigue failure. The Energy Institute guidelines are based on the Carucci-Müller [2] design curve and internal pipe sound power level equations are applied in the recommended analysis/screening methodology. The assessment are expanded to include consideration of fatigue life curves for range of pipe

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fittings and piping materials. Therefore, in this study, the calculation of sound power level with reference to the guideline by the Energy Institute, UK was used to determine the source of AIV in the piping systems. Estimates of the sound power level and the likelihood of fatigue failure would be used to redesign the main pipeline at the small-bore connections (SBC).

## II. METHODOLOGY

### A. *The Determination of Sound Power Level (PWL)*

In this study, the sound power levels were calculated using the Guidelines for the Avoidance of Vibration Induced Fatigue in Process Pipework of the Energy Institute [1]. The sound power level was calculated at the sources where the vibration was generated because the sound power level is the primary function of the upstream conditions. These sources included the blowdown valve (BDV), choke valve (IVA), Flow Valve (FV), Pressure Safety Valve (PSV) and Restriction Orifice (RO). The mass flow rate differed at each relief valve due to the staggered opening of the relief valve during an over-pressure scenario. In this case study, 30 pressure-reducing valves were evaluated.

Meanwhile, the flow noise along a length of pipe attenuates to some degrees because of viscous losses and heat conduction at the pipe wall. This attenuation is generally about 3 dB per 50 pipe diameters [1]. The pipe length was assumed to be 1 m in the present study (conservative assumption). As the pipe length between the valve and high risk locations of the valve increases, acoustic energy may be decreased to an acceptable level [1]. The PWL at the branch connection was calculated for seven pressure-reducing devices over the 1-m length. These devices were BDV 3802, IVA 0111, PSV 1221, PSV 3850A, PSV 4032, PSV 7021A/B, and RO 3809.

The acoustic analysis was streamlined to a single pressure drop source by calculating the sound power level (PWL) as in (1), which was then compared with the allowable power level ($PWL_{allowable}$) as in (2). The PWL was dependent on the process parameters, including the mass flow rate, pressure drop, gas temperature, and gas composition. However, there was just one parameter affecting the $PWL_{allowable}$, namely the diameter-to-thickness ratio.

The PWL at Source:

$$PWL = 10\log_{10}\left[\left(\frac{P_1-P_2}{P_1}\right)^{3.6} W^2 \left(\frac{T}{Mw}\right)^{1.2}\right] + 126.1 \qquad (1)$$

where,

PWL : internal pipe sound power level (dB);
$P_1$ : upstream pressure (bar abs);
T : upstream gas temperature (K);
W : gas flow rate (kg/s);
$P_2$ : downstream pressure (bar abs);
Mw : molecular weight of flowing gas.

If the calculated PWL value exceeded that of the $PWL_{allowable}$, then the piping system might be susceptible to AIV. If the PWL exceeded 155 dB, the PWL of the mainline discontinuity must also be determined, as in (3).

The $PWL_{allowable}$:

$$PWL_{allowable} = 173.6 - 0.125\left(\frac{D_2}{t_2}\right) \qquad (2)$$

where,

$D_2$ : inside pipe diameter, mm
$T_2$ : pipe thickness, mm

The $PWL_{(discontinuity)}$ of the mainline:

$$PWL_{discontinuity} = PWL_{source} - 60\,\frac{L_{dis}}{D_{int}} \qquad (3)$$

where,

$L_{dis}$ : Distance between source and the asymmetric welded discontinuity, mm
$D_{int}$ : Internal diameter of the main line, mm

### B. *The Determination of Likelihood of Failure (LOF)*

Meanwhile, the LOF was calculated using (4) to (8) following the guidelines of the Energy Institute [1]. The assessment generated a mainline LOF value at each welded discontinuity, e.g., small-bore connection, welded tee, or welded support. Corrective actions would be needed at the discontinuities when their LOF values equal to one.

Using the PWL at the location of interest,

$$Log_{10} N = 470711.5155 - 63075.1241\,(log_{10}B) + \frac{183685.4368}{\sqrt{B}} - \frac{575094.3273}{B^{0.1}} \qquad (4)$$

where,

$$B = a(PWL - 0.11276(s) - 0.001812(s)^2 + 4.307277 \times 10^{-5} \qquad (5)$$

$$s = 9.19 - \frac{D_{ext}}{T} \qquad (6)$$

$$a = 3.28 \times 10^{-7}\left(\frac{D_{ext}}{T}\right)^3 - 0.8503 \times 10^{-5}\left(\frac{D_{ext}}{T}\right)^2 + 7.063 \times 10^{-3}\left(\frac{D_{ext}}{T}\right)^1 + 0.816 \qquad (7)$$

Depending on the types of connections used, such as the welded type fitting, piping material duplex, or none, the number of cycles to failure, N calculated, was then multiplied with fatigue life multiplier for stage (FLM). Finally, the LOF was calculated using (8), and Table I shows the LOF values upon which the redesign of the piping system could be based. Where applicable, the calculated LOF values were then confirmed with Eisinger's design limit curve [2], in which the allowable design-limit and fatigue-limit lines were constructed based on (2).

$$L_f = -0.1303\ln(N) + 3.1 \qquad (8)$$

TABLE I. ACTION NEED TO BE TAKEN BASED ON LOF SCORE

| LOF Score | Action on Main line |
|---|---|
| LOF = 1 | Main line shall be redesigned by a specialist, re-supported or detailed analysis of the main line shall be conducted, vibration monitoring shall be undertaken, small bore connection (SBC) shall be examined, and visual survey shall be undertaken to check for poor construction |
| 0.5<LOF<1 | Piping integrity improvement should be applied (see the conclusion), vibration monitoring shall be undertaken, SBC shall be examined, and visual survey shall be undertaken to check for poor construction. |
| 0.3<LOF<0.5 | SBC shall be examined, and visual survey shall be undertaken to check for poor construction. |

### *C. Redesigning the Mailine at Small-bore Connection*

For pressure-reducing devices that failed the AIV screening (LOF > 0.5), further analysis was carried out to reduce the vibration. The model's view of the pressure-reducing devices experiencing fatigue failure was built with the computer programme SolidWorks and exported to ANSYS for dynamic stress analysis. Finite element analysis (FEA) was then used to simulate the piping vibration excited by the pipe internal sound dynamic pressure, the piping dynamic stress resulting from the vibration was also estimated.

## III. RESULTS AND DISCUSSION

### *A. The PWL at the Sources*

The study's result has been presented as Sound Power Level (PWL), which captures the generation and propagation of acoustic energy in the affiliated gaseous systems. The sound power level was calculated firstly at where the source of vibration generated, which at blowdown valve (BDV), choke valve (IVA), Flow Valve (FV), Pressure Safety Valve (PSV) and Restriction Orifice (RO). The mass flow rate from each relief valve was different due to the staggered opening of the relief valve during an overpressure scenario. In the first phase of AIV screening, seven out of the 30 examined pressure-reducing valves generated a PWL higher than 155 dB each, and hence requiring further evaluation on their LOF values in accordance to Energy Institute guideline. These seven devices were BDV 3802, IVA 0111, PSV 1221, PSV 3850A, PSV 4032, PSV 7021A/B, and RO 3809 as shown in Table II.

The PWL of each source calculated using (1) according to EI guideline and most of the sound power levels calculated are lower than limit criteria (155 dB). This means no further assessment is needed since the LOF is less than 0.30 where the systems are considered acceptable, and no further investigations required. A higher mass flow of compressible gas moving towards the reducing devices produced a higher PWL. Since the pressure-reducing devices reduced the gas pressure, the downstream pressure was low compared to upstream pressure. Therefore, if the differences between upstream pressure and downstream pressure were not high, this parameter shall not significantly affect the value of the PWL. The values of temperature and gas molecular weight also showed a similar trend for each pressure-reducing device, thus, the PWL values shall not be significantly affected.

TABLE II. 1ST PHASE OF AIV SCREENING AT SOURCE

| Tag No | Mass Flow, W (kg/s) | Upstream Pressure, P1 (barg) | Downstream Pressure, P2 (barg) | Gas Molecular Weight, Mw | Upstream Temperature, K | Sound Power Level, PWL (dB) |
|---|---|---|---|---|---|---|
| BDV 3802 | 40.21 | 118.20 | 4.60 | 20.44 | 343.15 | 170.61 |
| IVA 0111 | 8.14 | 165.50 | 15.10 | 21.1 | 373.15 | 156.08 |
| PSV 1221 | 8.82 | 226.60 | 3.40 | 20.44 | 318.23 | 157.49 |
| PSV 3850A | 11.76 | 43.80 | 7.30 | 20.29 | 351.07 | 157.83 |
| PSV 4032 | 12.77 | 182.05 | 5.30 | 21.44 | 306.98 | 160.11 |
| PSV7021A/B | 14.48 | 154.00 | 4.00 | 20.39 | 296.95 | 161.33 |
| RO 3809 | 60.67 | 118.60 | 13.70 | 19.08 | 359.60 | 173.38 |

### *B. Determination of PWL over the Pipe Length to the Branch Connection and LOF*

Table III shows the LOF values for the small-bore connection of the tagged pressure-reducing devices, with four devices (Tag no.: IVA 0111, PSV 1221, PSV 3850A, and PSV 4032) showing a 0.29 value each. These four pressure-reducing devices passed the AIV screening since their PWLs at the discontinuities were lower than the $\text{PWL}_{\text{allowable}}$.

TABLE III. 2ND PHASE OF AIV SCREENING - DETERMINATION OF LOF

| Tag No | Diameter of Pipe, D (mm) | Thickness, T (mm) | PWL@discontinuities (dB) | D/t | Allowable PWL (dB) | Pass/Fail | Likelihood of Failure, LOF |
|---|---|---|---|---|---|---|---|
| BDV 3802 | 150.00 | 10.00 | 170.10 | 15.00 | 171.73 | Fail | 0.29 |
| IVA 0111 | 150.00 | 6.35 | 155.05 | 23.62 | 172.14 | Pass | 0.29 |
| PSV 1221 | 80.00 | 7.11 | 157.10 | 11.25 | 170.96 | Pass | 0.29 |
| PSV 3850A | 150.00 | 6.35 | 160.60 | 23.62 | 170.96 | Pass | 0.29 |
| PSV 4032 | 200.00 | 14.28 | 160.11 | 14.00 | 172.14 | Pass | 0.29 |
| PSV7021 A/B | 200.00 | 37.90 | 160.80 | 5.28 | 170.08 | Pass | 0.29 |
| RO 3809 | 323.80 | 14.27 | 173.00 | 22.69 | 170.76 | Fail | 0.76 |

The allowable sound power level (PWL) is based on each of the reducing valves discontinuities ratio of the diameter of the mainline to the thickness. If the LOF value is $\leq 0.3$, the piping system is considered subsuming within the design limits [1], and the PWL produced is insufficient to cause any fatigue failure to the branch or the source of vibration. Although the calculated LOF value for BDV 3802 was 0.29, SBC might still be necessary, and a visual survey should be undertaken to check for poor construction. In contrast, the LOF value for RO 3809 was higher than 0.5, indicating that piping improvement would be essential.

Further analysis by using Eisinger's method to confirm the values of LOF calculated. The value of the sound power level of RO 3809 has exceeded the allowable design limit while BDV 3802 slightly below the line of the allowable design limit. Fig. 1 shows that the maximum allowable design and fatigue limit decreased as the diameter-to-thickness ratio increased, suggesting that diameter-to-thickness ratio inside the pipe (D/t) merely affected the vibration stress level at the external pipe wall with constant wall thickness. Thus, the wall thickness, rather than D/t, appeared to be the crucial factor upon which the AIV evaluation was dependent [6].

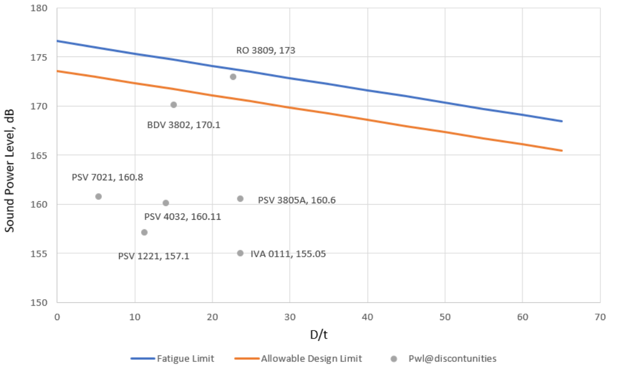

Figure 1. Eisinger's Method PWL allowable

For lines that score LOF ≥ 0.3, reparative action steps should be taken into consideration to improve piping integrity. The EI Guidelines offer several options to achieve a reduction in LOF. The line pipe is considered acceptable, and no action required if the LOF < 0.3. If the LOF falls between 0.3 and 0.5, a visual study should be applied to check for poor development/geometry/support for the primary line. Modifications to the mainline are not required, and small-bore connection actions should be undertaken. If the calculated LOF is between 0.5 and 1.0, a visual study should be attempted to check for poor development/geometry/support for the primary line. The mainline should be redesigned or re-supported for associated piping as far as practicable. Small bore connection (SBC) actions shall be undertaken. If LOF equals 1, a visual study should be done to identify the inadequate construction and support for the main line. If LOF cannot be reduced to less than 1 through changing the stiffness regime alone, the alternative options are to reduce the flow rate or increase pipe size/wall thickness [1].

### *C. Redesign of Pipe Mainline at Small-bore Connection (Discontinuities).*

Given that line RO 3809 failed the AIV screening (LOF > 0.5), it was chosen as a model for further analysis to reduce the vibration caused by the PWL. Fig. 2 shows the model's view of RO 3809 built with the software SolidWorks, in which, as a mitigation action, the thickness of the mainline was slightly increased by 16 mm to reduce the LOF. Additional information such as the actual discontinuity geometry and site visual condition was applied to FEA to model the discontinuity, reflecting the as-built conditions of piping. The specifications of the model are summarised in Table IV.

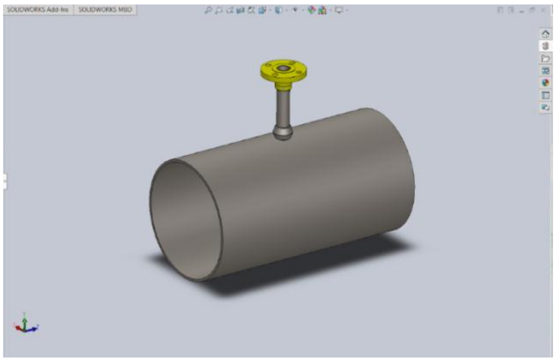

Figure 2. Design of SBC line downstream of RO3809

TABLE IV. PIPE MATERIAL AND SPECIFICATION

| | |
|---|---|
| Pipe Material | Carbon Steel |
| Yield Strength, | 241 MPa |
| Ultimate strength | 413 MPa |
| Diameter, mm | 323.8 |
| Thickness, mm | 30, 40, 50 |
| Frequency, Hz | 500 to 2500 |
| Poisson Ratio | 0.3 |
| Mass Flow kg/s | 30 |
| Pipe Length, mm | 1000 |
| Upstream Temp., K | 343.15 |
| Molecular Weight | 19.08 |
| Speed of Sound | 360450 mm/s |
| Modulus Elasticity, GPa | 195 |
| Upstream Pressure, barg | 118.6 |
| Downstream Pressure, barg | 1.37 |

Fig. 3 shows the mode shape of RO 3809 generated via the software ANSYS with the acoustic pressure mounted on the plate. The model was meshed before the analysis to calculate the von-mises stress at any point to determine whether the SBC was on dynamic or static loading. In Fig. 3, the SBC was perfectly meshed with the pipe mainline to obtain the first five modes between the frequency of 500 Hz and 2500 Hz. The thickness was then varied from 30 mm, 40 mm, and 50 mm to generate the maximum stresses in frequency, as shown by the peak in red (Fig. 3).

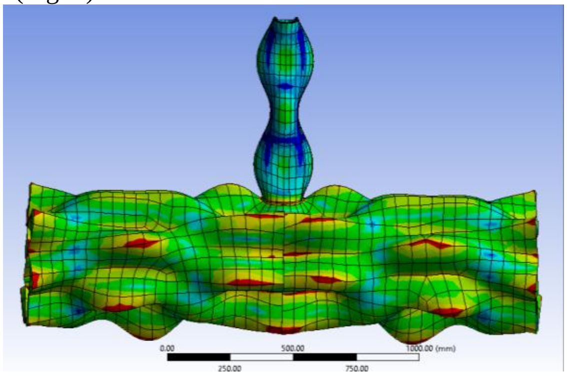

Figure 3. Pipe shell mode vibration of SBC @ 30mm

Fig. 4 shows the plot between the stress and the frequency. As a mitigation measure, the thickness of the piping was increased to 30 mm with peak stress of 70.4

MPa exerted by the PWL of 175 dB at a frequency of 1300 Hz. Although the stress was reduced to the safe design limit, i.e., < 105 MPa [7], the von stress contour indicated that the design was still susceptible to fatigue failure with red contour (Fig. 3). The graph gradually decreased after it peaked, yielding the minimum stress at 3.3 MPa at 2100 Hz, at which fatigue failure would most unlikely happen.

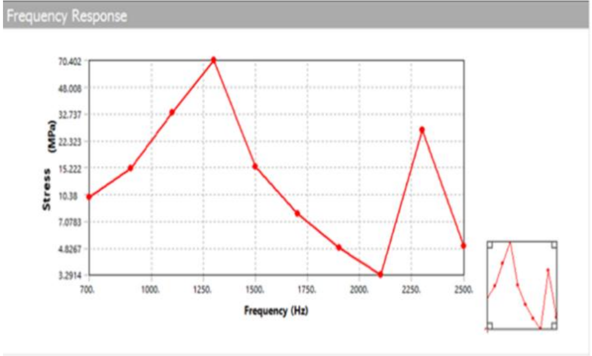

Figure 4. Stress vs Frequency @ 30mm of thickness

Fig. 5 shows that when the thickness of the piping was increased to 40 mm, which was thicker than the actual thickness by 26 mm, less fatigue was exerted around the branch and the main pipe with lesser red contour. A decrease in stress was primarily due to a slight decrease in the D/t ratio. Fig. 6 shows that the maximum stress of the design at 1300 Hz was 52.8 MPa with a thickness of 40 mm, which was lower than the maximum stress for the thickness of 30 mm. Clearly, fatigue failure was less likely to occur when the stress was low, resulting in a higher number of cycles to failure.

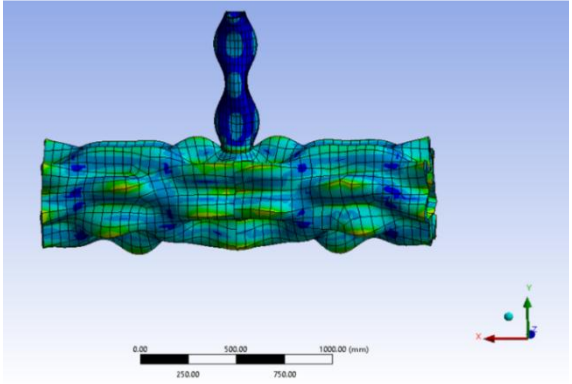

Figure 5. Pipe Shell Mode Vibration of SBC @ 40mm, 175 PWL

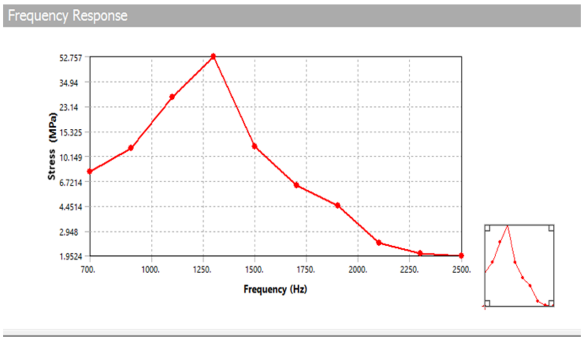

Figure 6. Stress vs frequency @ 40mm of thickness

Fig. 7 shows that when the main pipe's thickness was increased to 50 mm, there was no high concentration of stress at the SBC or around the main pipe. The maximum stress obtained at 1300 Hz was the highest, i.e., 26.4 MPa, and it was substantially lower than the design limit for carbon steel, namely 105 MPa [7], as shown in Fig. 8. The stress gradually decreased, reaching its lowest value, namely 0.97 MPa at 2500 Hz. The dynamic stress was then compared with the fatigue life curves in accordance with ASME VIII Div. 2[8] and BS 7608 [9] for calculating the pipe discontinuity fatigue life. These limits were determined based on the device operating duration and the material type of the pipe discontinuity [7]. Based on the input of acoustic energy used, each of the stress was simulated to determine the number of cycles to failure. The higher the number of stress, the lower the number of cycles to failure and hence resulting in higher LOF values.

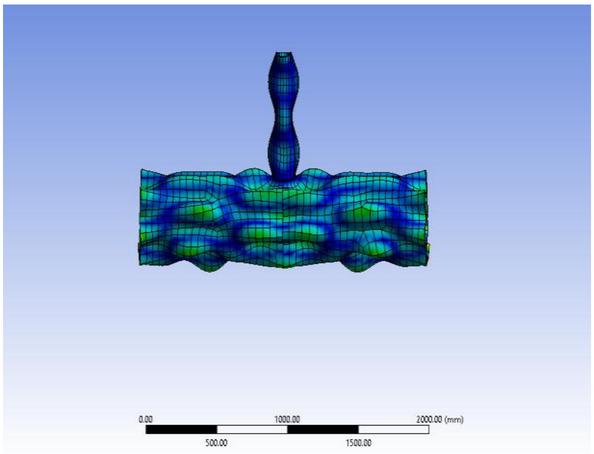

Figure 7. Pipe shell mode vibration of SBC @ 50mm, 175 PWL

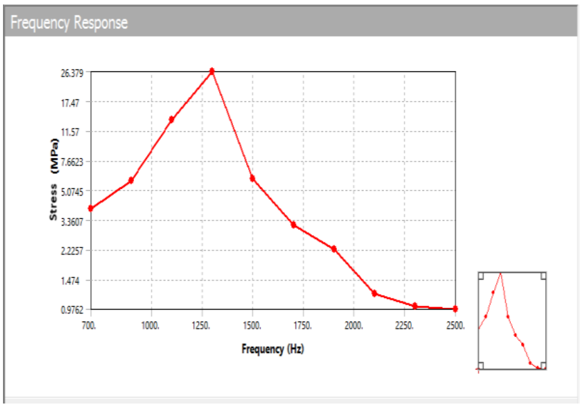

Figure 8. Stress vs Frequency @ 50mm of thickness

Table V shows the LOF at RO 3809 before and after the countermeasure at different thicknesses. After the countermeasure, the LOF decreased as the thickness of the mainline increased. The wall thickness increment has the effect of vibration stress level decrease a little more significant than the effects of wall thickness and pipe diameter ratio to wall thickness [6]. While the thickness was increased to 30 mm, 40 mm, and 50 mm, their respective LOF value had reduced from 0.76 to 0.54, 0.42, and 0.29. Even though the PWL applied to the design was

175 dB, the vibration stress decreased as the thickness increased. With a LOF value of 0.29 (< 0.3), the pipe now could withstand the PWL produced at the discontinuities with minimal fatigue. This level of stress was reduced through the implementation of design actions, which increased the connection quality level and finally yielded an increased number of cycles to failure, N, through the same curves. In practice, increasing wall thickness would have a massive impact on the piping system's overall weight. Increasing the wall thickness would also decrease the internal cross-section area thus increasing the flow rate. Hence, proper re-evaluations would be required to further mitigate this phenomenon.

TABLE V. RESULT OF AIV ASSESSMENT BEFORE AND AFTER COUNTERMEASURE.

| Tag No | Pipe Diameter, D (mm) | Thickness, t (mm) | D/t | Likelihood of Failure (LOF) |
|---|---|---|---|---|
| RO 3809 | 323.8 | 14.00 | 23.13 | 0.76 |
| RO 3809 (After counter measure) | 323.8 | 30.00 | 10.79 | 0.54 |
| RO 3809 (After counter measure) | 323.8 | 40.00 | 8.10 | 0.42 |
| RO 3809 (After counter measure) | 323.8 | 50.00 | 6.48 | 0.29 |

## IV. CONCLUSION

The problems of AIV could be addressed at the design stage, at which the acoustic level could be estimated, and the required adjustments could be implemented to eliminate or mitigate the potential of vibration failure due to excessive excitation. The Energy Institute guideline provides a stepwise approach via qualitative assessment to identify the potential excitation mechanism while providing a ranking order to prioritise the subsequent assessments. In this study, a quantitative assessment was carried out to determine the LOF of vibration-induced piping fatigue in areas of higher risks. By calculating the pipe fatigue life, the risk was quantified to evaluate the extent of physical modifications required to mitigate AIV. In this respect, incrementing the wall thickness yielded a significant improvement in acoustic fatigue life. For typical piping integrity improvement over the welded branches with high potential for acoustic vibration-induced fatigue failure, the usage of weldolets, especially on thin-walled pipe, should be avoided. Instead, sweepolets or pressure-reducing tees were recommended.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

Mohd Fazril Irfan and Muhammad Shalihan wrote the paper and conducted the research; Ahmad Danial Zulhilmi and Zulkifli analysed the data and provided some concepts, review and discussion. All authors had approved the final version.

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**Zulkifli Abdul Rashid** is an Associate Professor at UITM. He attained his first degree in chemical engineering at University of Manchester Institute of Science and Technology (UMIST) UK. After graduated, he works as a project engineer and project manager for about 3 years in a few oil and gas companies. The petrochemical projects which he participated were insulation project at UCC plant in Kertih, Terengganu, fabrication and maintenance sphere tank at BP mobil in Klang, Selangor and PETRONAS, Melaka. During his service at Department of Environment (DOE), he directly involved in various enforcement activities such as prosecutor officer, assess hazardous material installation projects, river rehabilitation project evaluation, analyze the reliability and performance of industrial wastewater and air pollution control system. Whilst at DOE, he pursued his study in MSc Eng (Env Eng) at UPM and after 5 years, he joined UiTM. He holds his PhD from UTP in Process Safety and Loss Prevention. In UITM, he involved in various projects such as assessment RDF technology for KPKT, hazardous area classification zoning ATEX, IEC BSI, and research associated with process safety and quantitative of risk assessment, CIMAH consultancy works, major accident prevention, and collaborative research in industrial safety and environmental management at local and overseas.