# VIBRATION INDUCED FATIGUE FAILURE PREDICTION IN PROCESS PIPEWORK

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***Abstract*— The vibration in piping system has been a great threat in industry. This vibration has become a leading source of pipe failure especially in oil and gas industry with 21% of the pipework failure on the topsides facilities were due to vibration and fatigue failures in the North Sea of UK, reported by the UK's Health & Safety Executive (HSE). Due to this, it is needed to verify whether the targeted area of observation really have high possibilities of flow induced vibration (FIV), earlier from designing stage. Other issues that need to be focused on are to identify best suitable means to reduce FIV and verify whether the recommended action is effective enough to reduce and cope failure in piping system. This research aims to identify potential FIV which can lead to fatigue failure if excessive. Following the guideline published by Energy Institute on the Avoidance of Vibration Induced Fatigue Failure (AVIFF), the assessment was done accordingly. From qualitative and quantitative assessment until the process of simulating the piping system through simulation software based on the recommended action identified, the processes were done following all the required steps. By calculation and detailed analysis, several lines were identified to have high failure potential. By using computational fluid dynamic (CFD) and finite element analysis (FEA), the simulation models of the piping system were produced. Changes to the pipe nominal diameter and wall thickness were applied to the effected lines. After changes applied, simulation was repeated with CFD tools and it was verified that changes made were able to reduce vibration on the line.**

***Keywords*—** *Computational fluid dynamic (CFD), finite element analysis (FEA), flow induced vibration (FIV).*

## I. INTRODUCTION

Piping system is an assembly of various components function to transport fluid from one location to another. In oil and gas industry, transportation of hydrocarbon through piping requires a proper measure and observation because of the variation in the velocity and pressure of the hydrocarbon. On the topside facilities, the process pipework need to be assessed properly ensuring safe flow from the start till the end process. Any damage can cause unwanted incident to happen on the site.

Vibration problems have obstructed many smooth operations in the industrial plants due to fluid flow. If it is serious, this phenomenon can lead to a significance loss in the productivity as the process require frequent maintenance and repairing which resulted in high cost investment. Vibration has been a threat to the piping system since it can lead to a sequence of event that can damage the system or even all the facilities. It has been reported by the UK's Health & Safety Executive (HSE) for offshore industry that in the UK sector of the North Sea, 21% of the topsides pipework failure were due to vibration and fatigue failures.

This flow-related vibration is generally known as flow-induced vibration (FIV). Fatigue failure in process piping caused by vibration is due to the change of mechanical energy excited by the movement of fluid to noise. FIV is a common phenomenon that can lead to vibration induced fatigue failure. FIV is caused by the internal fluid structure interaction due to pressure fluctuation and momentum exchange of the fluid flow and the structure. The Norwegian Petroleum Safety Authority has reported the instance of fatigue failure that possibly coming from FIV which have resulted in pipe damage.

In this study, qualitative and quantitative assessments are the techniques that are used to analyze on the oil and gas piping system. Qualitative assessment is the process of identifying the potential excitation mechanism that may exist and provide means of rank ordering of the process systems or units. By observing the overall piping system through the process and instrumentation diagram (P&ID), the high possible area of FIV like small bore connection (SBC), branch connection and welded pipe support need to be assess in detailed to identify the excitation of vibration mechanism. Quantitative assessment is taken from the excitation mechanism identified from the qualitative assessment (Moustafa, 2010). The method is by calculating the likelihood of failure (LOF) of the area identified, analyzing the degree of failure of that certain piping area. LOF is a method of analysis by calculating the tendency of piping to experienced failure subjected to the vibration. LOF of less than one is required to ensure that the pipe is safe. This failure in piping must be analyzed frequently because it is important to understand on the mechanism vibration on the pipe so that precaution steps can always be taken in any circumstances. The LOF calculation makes it easier to identify the degree of failure in piping and at each different section this degree of failure can be compared to identify which one requires attention first.

Computational Fluid Dynamics (CFD) simulation is a local flow modeling of specific phenomenon to assess flow mechanisms and input. Finite element analysis (FEA) is the modeling systems in virtual to identify and fix any potential performance issues of that certain system. It is a frequent mode of piping system analysis. Through this type of analysis, the behavior and ability of a piping system with the flow mechanism is predicted.

In order to battle FIV, CFD analysis was done to get a clearer view on the fluid flow pattern and the impact of the flow to the structure. Several changers made directly to the structure design through this analysis produces better output which can reduce vibration excitation on the structure causes by the fluid flow.

Combination of CFD simulation and FEA can be implemented as early as possible in the designing stage or to be used later to refine an existing system, ensuring the design to qualify the specification needed.

## II. METHODOLOGY

The assessment was done accordingly based on guideline provided by EI. A summary on the methodology is shown by flowchart in Figure 1.

### A. *Qualitative Assessment*

Qualitative assessment is the method that involves the process of identifying the possible excitation mechanism and the assessment on the high possible area to be excited. Before starting a survey on the piping system, a preparation should be done in order to identify the most affected area on the piping scheme. The key information that required for this assessment are the process flow diagram (PFD), piping and instrumentation diagram (P&ID) and knowledge on the plant operation. Basically, this assessment is a rough method of determining tendency of pipeline to experienced failure causes by flow induced vibration.

P&ID analysis

A layout of the piping scheme has to be observed to identify the spot or area that needed to be studied and observed in detail. All information about the piping system includes the flow parameters have to be collected for this assessment. After all the information regarding the piping system including the scheme have been studied, the assessment can be done accordingly. The area with high possibility of failure will be selected and the assessment will continue further. A rough observation through P&ID was done to ensure all lines involve were safe and not susceptible to FIV.

Screening analysis on main line

The flow kinetic energy of the area which has possibilities of producing FIV was calculated to enable the process of ranking the failure into low, medium or high. The likelihood of failure is classification is shown in Table 1 below. This flow kinetic energy calculation is a first procedure before proceeding with detailed analysis if the pipe has possibility to experienced failure.

Table 1 Likelihood classification

| **Likelihood Classification** | **Range (kg/ms$^2$)** |
|---|---|
| Low | $\rho v^2 < 5000$ |
| Medium | $5000 \leq \rho v^2 < 20000$ |
| High | $\rho v^2 \geq 20000$ |

## B. *Quantitative Assessment*

Quantitative assessment is a scoring method which involves calculation of the probability of failure of the piping system on the specific area identified based on previous qualitative assessment. The scoring method is called Likelihood of Failure (LOF).

Detailed analysis on main line

LOF calculation was done to determine either the main line required changes or can be maintained at initial condition. The LOF is divided into several ranks which will determine the actions needed to be applied on the line. Table 2 below shows the LOF rank and actions needed to reduce and cope failure.

Table 2 Actions on main line

| **Rank** | **Actions needed** |
|---|---|
| LOF > 1 | Modification and inspection on main line |
| 0.5 < LOF ≤ 1 | Monitor and inspection on main line |
| 0.3 ≤ LOF < 0.5 | Check the SBC connection |
| LOF < 0.3 | No change required |

There are several steps and calculation needed to obtain the LOF value of a line.

i. Fluid Viscosity Factor (FVF) determination

Table 3 FVF based on type of fluid

| **Type of fluid** | **FVF** |
|---|---|
| Liquid & multi-phase | 1 |
| Gas | $FVF = \frac{\sqrt{\mu_{gas}}}{\sqrt{1 \times 10^{-3}}}$ |

ii. Support arrangement determination

The support arrangement can be divided into four types; stiff, medium stiff, medium and flexible. For this assessment, based on the figure and system, it was assumed that the line and all the system have a flexible support system.

iii. Flow induced vibration factor ($F_v$) determination

The $F_v$ is determined based on the support arrangement clarified before. For the system with flexible support system, the $F_v$ is calculated using formula provided in Table 4.

Table 4 Methods of calculating Fv

| **Range of outside diameter** | **$F_v$** | **α** | **β** |
|---|---|---|---|
| 60mm – 219mm | $\alpha(\frac{D_{ext}}{T})^{\beta}$ | $1.32 \times 10^{-5} 646 {D_{ext}}^2 + 4.42 \times 10^{-3} D_{ext} + 12.22$ | $2.84 \times 10^{-4} D_{ext} - 4.62 \times 10^{-7} {D_{ext}}^2 - 0.164$ |
| 273mm – 762mm | | $41.21 D_{ext} + 49397$ | $0.0815 \ln(D_{ext}) - 1.3842$ |

iv. LOF

After all other parameters have been identified, the LOF is calculated using the following equation;

$$\text{Flow Induced Turbulence LOF} = \frac{\rho v^2}{F_v} FVF$$

Detailed analysis on SBC

Similar with main line, the LOF is divided into several ranks which will determine the actions needed to be applied on the line. Table 5 below shows the LOF rank and actions needed to reduce and cope failure on SBC.

Table 5 Actions on SBC

| **Rank** | **Actions needed** |
|---|---|
| LOF > 0.7 | Remove SBC |
| 0.4 ≤ LOF < 0.7 | Monitor and inspection on SBC |
| LOF < 0.4 | No change required |

The LOF calculation for SBC was divided into two parts; LOF geometry and LOF location. Table 6 and 7 below shows the scoring value applied for this assessment in order to identify the SBC LOF. The minimum value of LOF from both geometry and location LOF will be taken as the LOF modifier. The main line LOF was times with 1.42. The value obtained was compared with the LOF modifier and the minimum between these two values is considered to be LOF SBC.

Table 6 LOF geometry determination

| **Line no.** | **7, 21, 22, 23** | |
|---|---|---|
| | **Value** | **Score** |
| Type of fitting | Threadolet(FBW) | 0.9 |
| Overall length of branch | <200mm | 0.1 |
| No & size of valve | 1 | 0.5 |
| Parent pipe schedule | 160 | 0.3 |
| SBC min diameter | 2" ND | 0.5 |
| **LOFgeom** | | **0.46** |

Table 7 LOF location determination

| Line no. | 7, 21, 22, 23 | |
|---|---|---|
| | **Value** | **Score** |
| Location | Valve | 0.9 |
| Parent pipe schedule | 160 | 0.3 |
| **LOFloc** | | **0.6** |

### C. *Corrective action*

For this assessment considering that the support system and the flow parameters are constant, the corrective action or changes will only applied to the pipe nominal diameter and wall thickness. This type of changes normally related to turbulence flow analysis.

Based on the P&ID, all lines assessed were having the same initial diameter of 4" (100mm). The pipe sizing and wall thickness follows the pipe schedule of 160 as recommended in the P&ID provided. The changes done on the pipe size were all referred to ASME 36.10 pipe sizing chart. For valve, the sizing was referred to the ANSI Class 1500.

### D. *Modeling analysis*

The modeling analysis functions to verify all the calculations virtually through the fluid flow profile. By using Autodesk CFD, the flow of the fail line was simulate before and after changes have been made to make comparison and verify on the effectiveness after changes applied.

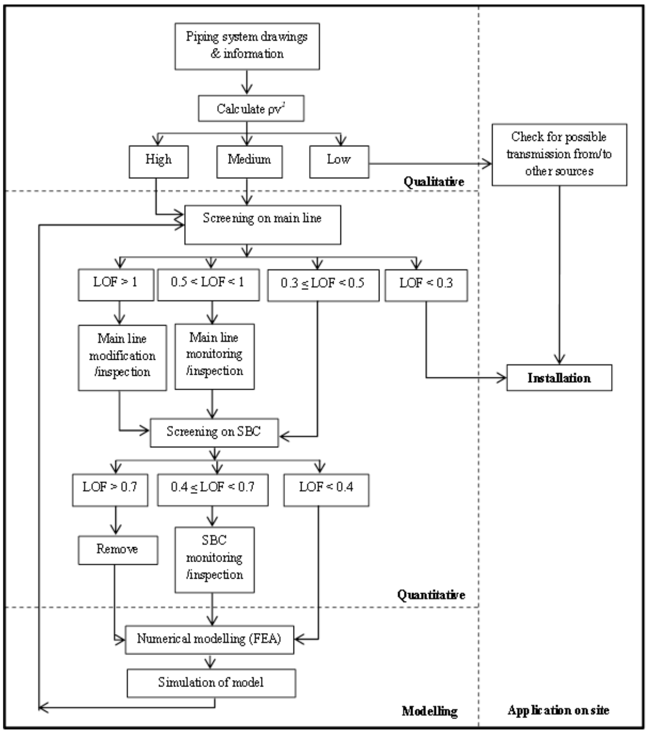


Fig. 1: Flow chart of methodology

## III. RESULTS AND DISCUSSION

### A. *Qualitative Assessment*

Based on data obtained from the P&ID, the measurements of the pipe were based on the ASME 36.10. After the correct measurement has been identified based on the P&ID, the process is continued with the screening process which involves calculation of the flow kinetic energy ($\rho v^2$) to identify the line which have tendency to cause failure. The values obtained were showed in tables below based on the number of trials. If the line experienced failure, the calculation is repeated with new piping design which involves the changes of pipe nominal diameter and wall thickness. More trials are needed if failure tends to occur although changes have been made. For the first trial, $\rho v^2$ was calculated for each line. For second trial, $\rho v^2$ was only calculated for the line which has experienced failure on the previous trial and the calculation is based on the changes applied to the line.

First trial

Line 7 have the value of $\rho v^2$ of 5538.06 kg/ms$^2$ and is classified to have moderate risk of failure. For line 21, 22 and 23, although the failure were ranked into Rank 1, the value of $\rho v^2$ which is 3078.88 kg/ms$^2$ is near to 5000 kg/ms$^2$ and have potential to experienced failure. Therefore, these lines were classified to have moderate risk as line 7 and included in the likelihood of failure (LOF) determination afterwards.

Second trial

Line 7 has value of $\rho v^2$ of 1067.22 kg/ms$^2$ while the other three lines (line 21, 22 and 23) have value of $\rho v^2$ of 593.32 kg/ms$^2$. These values were all under 5000 kg/ms$^2$ and can be classified to have low risk of failure. No further analysis needed for all lines.

### B. *Quantitative Assessment*

The quantitative assessment is the continuation of qualitative assessment. From the values obtained before, the line which has been identified to have potential failure was further analyzed by calculating the likelihood of failure (LOF) in this section. Table 8 and 10 are tables of LOF values calculated on main line and small bore connection (SBC), respectively.

LOF Main line

For the calculation of main line LOF, the lines were assumed to have flexible support.

Figure 2 and 3 shows the distribution of LOF based on cases. Line 7 is classified under Case 1, line 21 and 23 are classified under Case 2 and line 23 is classified under Case 3. The red dashed line in the figure act as a benchmark to the LOF value. Any cases with LOF higher than the line need further observation. If the LOF obtained is below the line then the pipe is safe to be used. The benchmark value is at LOF equals to 0.3.

Table 8: Comparison of main line LOF

| Line no. | 7 | 21 | 22 | 23 |
|---|---|---|---|---|
| Initial | 0.79 | 0.44 | 0.44 | 0.44 |
| Final | 0.14 | 0.08 | 0.08 | 0.08 |

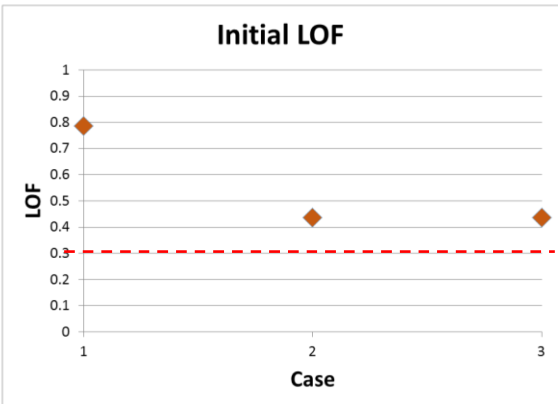


Fig. 2: Initial main line LOF

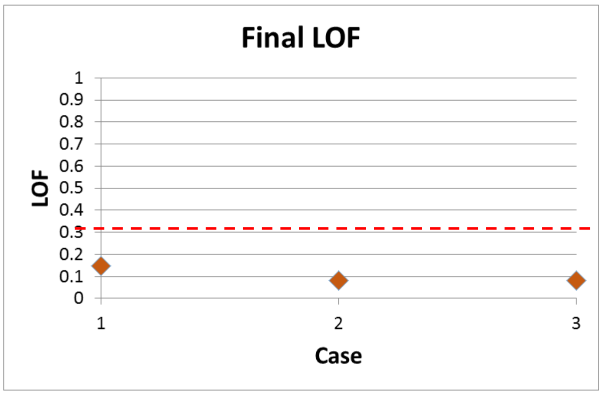


Fig. 3: Final main line LOF

Table 9: Actions taken on the main line

| Case | Initial | Actions | Final | Actions |
|---|---|---|---|---|
| 1 | 0.79 | Change pipe nominal diameter and wall thickness | 0.14 | No change required |
| 2 | 0.44 | | 0.08 | |
| 3 | 0.44 | | 0.08 | |

Based on Table 9, from initial LOF calculated, they showed that all lines required changes in the pipe thickness and the diameter for better flow. After changes have been implemented, the LOF reduce its value and the pipe is now safe.

LOF Small Bore Connection

Both LOF determined are assumed to be fine and no changes are taken on the SBC.

Table 10: Comparison of SBC LOF

| Line no. | 7 | 21, 22, 23 |
|---|---|---|
| Initial | 0.46 | 0.46 |
| Final | 0.20 | 0.11 |

## C. *Model analysis*

For the flow analysis, the flow was assumed to be in steady state. In CFD tools, the boundary condition applied for the analysis is the mass flow rate of the line. For Case 1, the mass flow rate is 9727 kg/hr while for Case 2 and 3 is 33193.776 kg/hr. Based on the parameters given for each line, the flow was analyzed by using Autodesk CFD. The analysis was done according to different cases divided based on the arrangement of the system.

From obtaining the initial value to the changes, the pipe sizing was according to sizing chart provided by ASME B36.10. The initial nominal diameter of all pipes in all cases is 4” (100mm). As failure tends to occur, the pipe nominal diameter was change to 6” (150mm). For the wall thickness determination, the pipe follows the initial schedule number of 160.

From the velocity contour shown by figures below, it can be said that the particle momentum and kinetic energy is changing throughout the pipe. When the fluid starts to enter the valve, the speed gradually decreases as the diameter of the valve is larger than the main line. The existence of the device cause disturbance to the flow regardless whether the flow is laminar or turbulent, steady or un-steady, causing flow induced vibration (Siba, 2016). The decreased in speed at the valve line affect the second part of the main line which is connected to the outlet of the valve. At this region, the velocity of flow tends to increase because of the smaller diameter pipe compared to valve. The higher the speed is, the larger the momentum effect on the main line which can rupture the line if the thickness cannot encounter the momentum. From Figure 4, it can be seen directly that when the diameter of the pipe is smaller, the velocity of the flow increases and tends to cause vibration. From the wall shear stress contour, the reduction in the value reduces stress on the pipe causing the pipe to lower frequency of vibration. For the area of valve, the high shear stress is disregards and assumed to be fine because based on the LOF calculation, the valve is susceptible from failure. Focusing on the main line changes only, the difference can easily and directly be seen by the contour of the wall shear stress.

Case 1

**Initial condition**

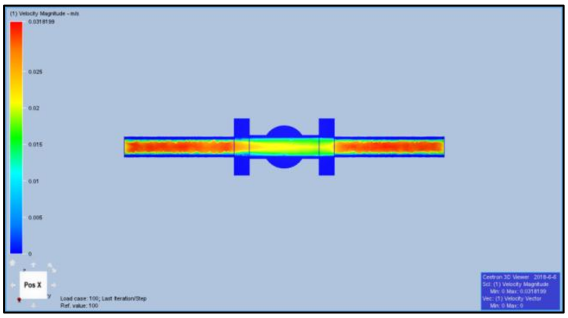

Fig. 4: Velocity contours of Case 1 with nominal diameter 100mm

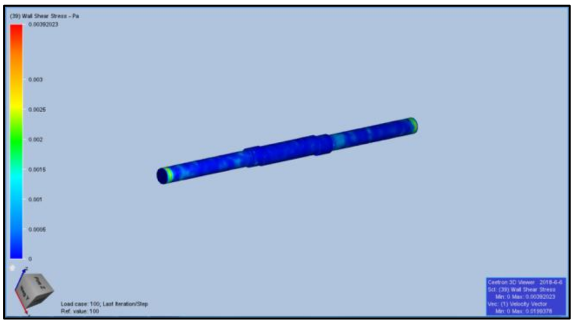

Fig. 5: Wall shear stress of Case 1 with nominal diameter 100mm

**Final condition**

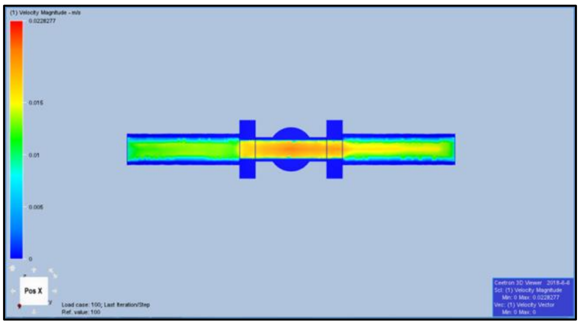

Fig.6: Velocity contours of Case 1 with nominal diameter 150mm

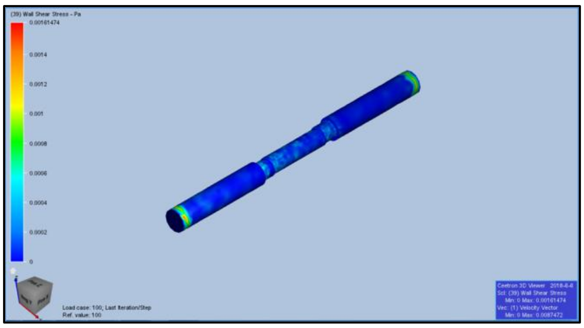

Fig. 7: Wall shear stress of Case 1 with nominal diameter 150mm

Case 2

**Initial condition**

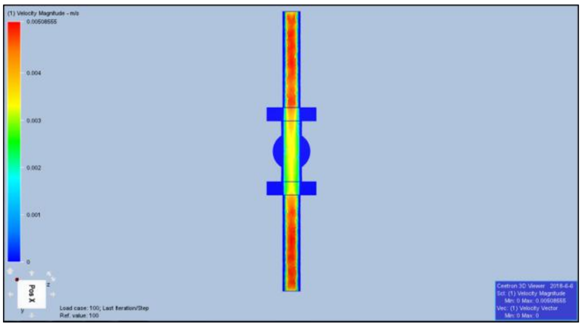

Fig. 8: Velocity contours of Case 2 with nominal diameter 100mm

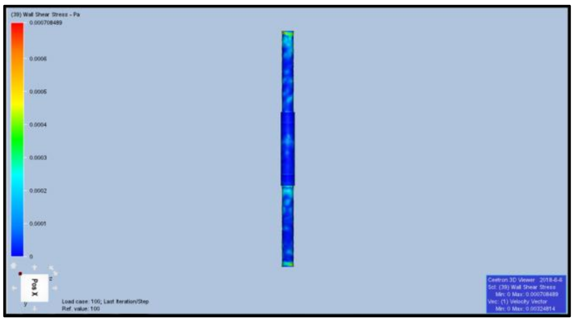

Fig. 9: Wall shear stress of Case 2 with nominal diameter 100mm

**Final condition**

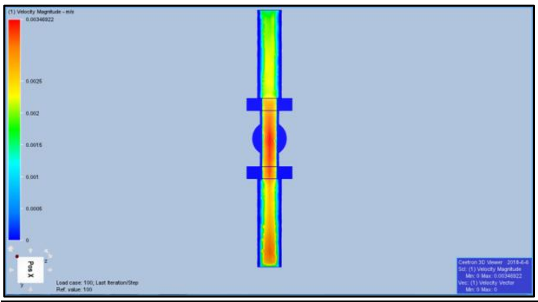

Fig. 10: Velocity contours of Case 2 with nominal diameter 150mm

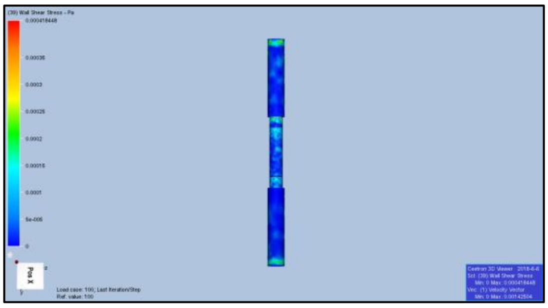

Fig. 11: Wall shear stress of Case 2 with nominal diameter 150mm

Case 3

**Initial condition**

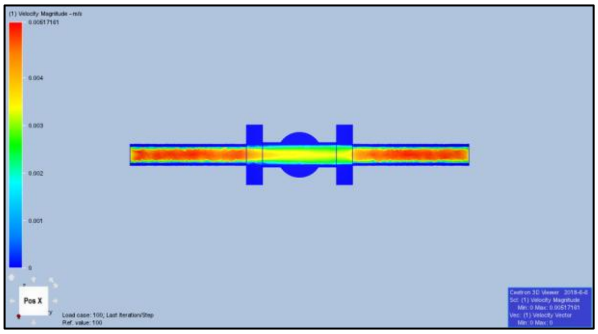

Fig. 12: Velocity contours of Case 3 with nominal diameter 100mm

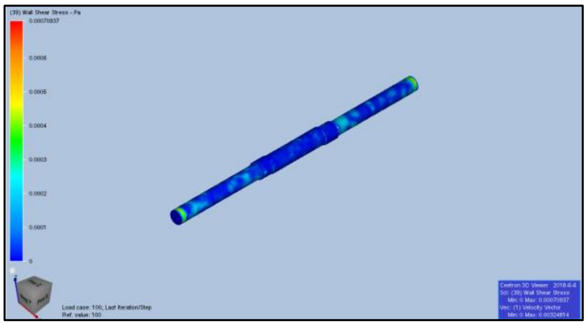

Fig. 13: Wall shear stress of Case 3 with nominal diameter 100mm

**Final condition**

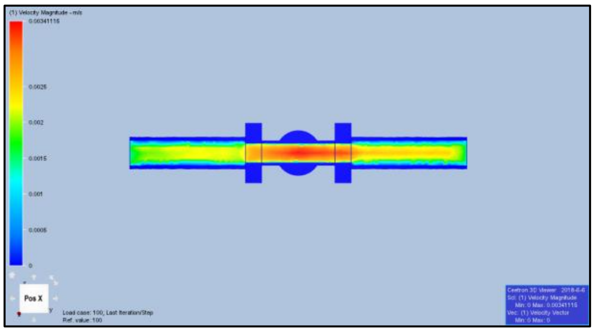

Fig. 14: Velocity contours of Case 3 with nominal diameter 150mm

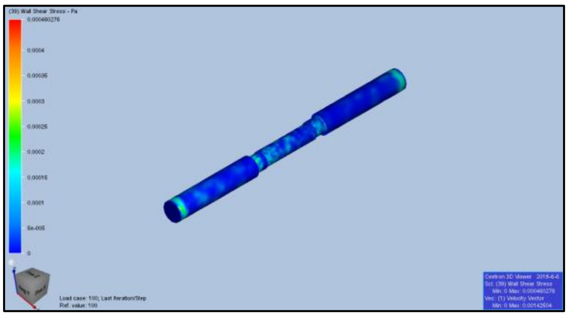

Fig. 15: Wall shear stress of Case 3 with nominal diameter 150mm

## IV. Conclusion

The objective of the study has been achieved successfully. The first objective is to identify area with FIV by calculating the likelihood of failure (LOF). Based on the Guideline for Avoidance of Vibration Induced Fatigue Failure (AVIFF) in Process Pipework provided by Energy Institute (EI), the calculation of LOF can be done successfully. Following the method of assessment, qualitative and quantitative assessment, the LOF rank and value were calculated and determined successfully.

The second objective is to recommend action to reduce failure in the piping system. For this study, the changes to piping system is only on pipe nominal diameter and its wall thickness, disregard any other parameters by assuming them to be constant although changes have been made. In analyzing flow induced vibration in piping system, the characteristic of the flow inside the pipe need to be monitored properly. From velocity and pressure changes, this flow can break pipe in any circumstance if no proper observation and monitoring is done. Both actions recommend are suitable to be applied on the system.

The last objective is to verify the action recommended by simulating the flow using simulation software. For this study the software used is Autodesk CFD. From the model analysis, a clearer view on the fluid flow can be seen instead of only calculation. This clear view make it easier to differentiate between two different situations ensuring either the changes made is suitable or not and also to validate the changes applied. From the simulation figure, it is verified that the changes made to all the lines is effective enough and can reduce the fatigue failure problem.

For overall it can be concluded that the study was done successfully. All the changes applied are suitable and can accommodate the LOF value calculated. The AVIFF method provided by EI is the most suitable method to identify and calculated the likelihood of failure on piping system. A clearer view of the flow can be seen through the simulation figure. For the changes in the velocity and pressure throughout the system, it can be seen directly from the graph plotted. To conclude this study, it can be said that by increasing the pipe nominal diameter and wall thickness, the failure caused by flow induced vibration can be reduced and cope.

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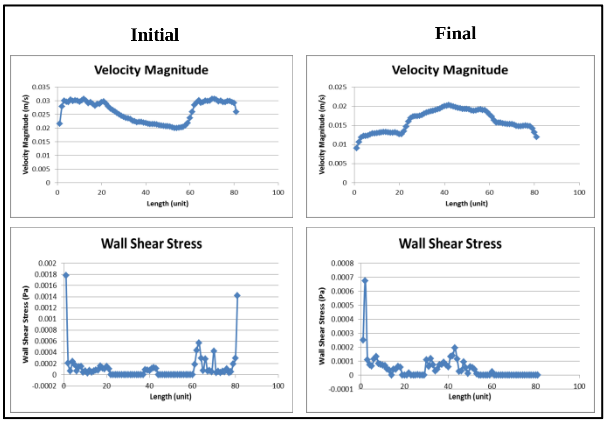


Fig. 16: Comparison of initial and final velocity and wall shear stress distribution for Case 1

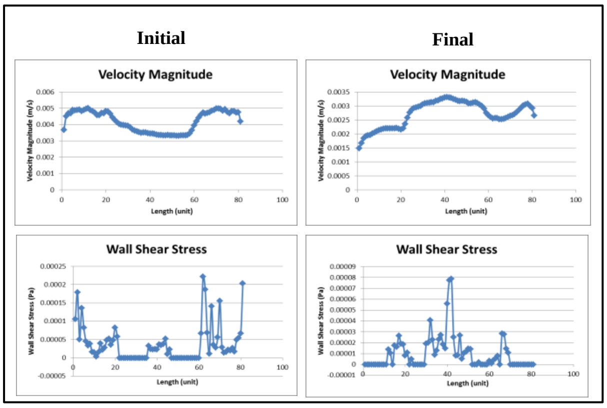


Fig. 17 Comparison of initial and final velocity and wall shear stress distribution for Case 2

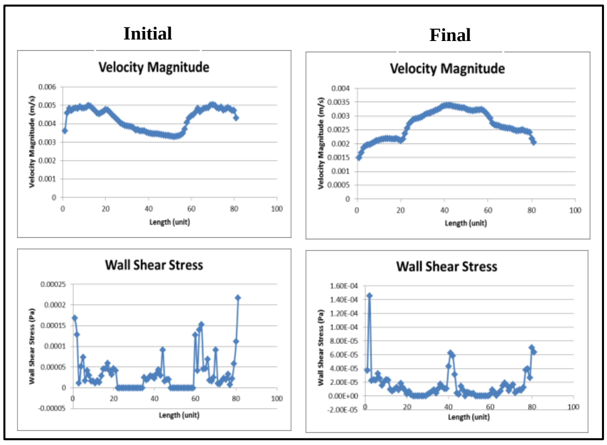


Fig. 18: Comparison of initial and final velocity and wall shear stress distribution for Case 3