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Experimental and Simulation Study of Vibration Effect on Pipeline at Uthm Biodiesel Pilot Plant

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Abstract: Vibration is an unavoidable reality in the design of pipe systems. The movement of the rotating equipment like compressor, pump, and fan can cause vibration on the pipeline system. The force from the rotating equipment produces the excitation force on the pipeline. This research is to study the vibration effect on the pipeline system at the centrifugal pump. In this study, the measurement of vibration on the pipeline was carried out by using a vibration analyzer. This experiment was conducted at UTHM Biodiesel Plant. Then, the simulation for analyzing the pipeline's vibration was carried out using the ANSYS Workbench software. The modal analysis and harmonic response on ANSYS were used to identify the pipeline natural frequency and frequency response. The speed of revolution per minute for the centrifugal pump motor is 2910 rpm and it is used as the rotational velocity for modal analysis. The rotating force produced by the motor at the centrifugal pump was 27.07 Nm. The rotating force was used for the simulation on harmonic response analysis to obtain the critical peak of the frequency response of displacement, velocity, and acceleration. This research is expected to obtain the maximum and minimum natural frequency, and also the maximum peak response of the pipeline. The different frequency will show the different behaviour of the pipeline on the modal analysis. The vibration produced from centrifugal pump was higher on horizontal direction compared to vertical direction based on the measurement on the pipeline at UTHM Biodiesel Plant. By investigating the impact of the rotating equipment on the pipeline, we were able to identify the maximum frequency for the pipeline based on the simulation and measure the vibration on the pipeline through the experiment.

Keywords: Vibration, ANSYS Workbench, Centrifugal Pump, Pipeline

1. Introduction

Issue related to vibration is not unusual in the pipeline industry. There are many causes and effects of vibration on a piping system. Vibration industrial machinery is the cause of a problem on pipe

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vibration. The piping vibration is caused by mechanical force from reciprocating and rotary equipment [1]. Pressure pulsations in pipelines also cause vibrations of piping structures. Often these pulsations may be very serious, causing damage to piping or other elements in a hydraulic device [2].

Pumps and compressors can cause a wide range of vibration problems, and the most exposed to the vibration issue is a piping system. Vibration problems are more often found in pumping and processing facilities due to the location of machinery. Vibration problems may result in fatigue failures and can cause compromising the integrity of the pipeline. Rotating or reciprocating equipment is typically the reason for vibration in the pipeline when equipment transmits energy to the pipeline through direct mechanical interaction, pressure pulsation, or turbulence in the pumped fluid. When the driving force excites a mechanical natural frequency or an acoustic natural frequency of the contained fluid or both, it can be caused the vibration to occur [3].

The vibration effect depends on the excitation frequency and stability of the piping system. The loads transferred to the pipe support increase as the vibration of the piping system increases. The vibration on a piping system also can cause damage to the mechanical seal [4]. The effect of piping vibrations can cause instrument distortion, pipe failure, and equipment damage. The higher vibration also can cause the damage of mechanical seal on the piping system. High vibration not only can cause fatigue failure and damage the structure of pipe, but it also causes loosen and rupture on connection part, as well as fracturing or even damage to measurement instruments, but they can also cause noise pollutions [5]. When the exciting frequency is beyond the range of the pipeline system's natural frequency, resonance occurs in the equipment and pipelines, resulting in significant damage to the equipment and pipelines [6]. Vibrations typically occur in rotating and reciprocal components due to complex effects of manufacturing tolerances, clearances, rolled and rubble contacts between system components, and off-balance powers. Sometimes, minor negligible vibration can also excite the resonant frequency of any other structural part and amplify into a large source of vibration and noise [7].

2. Methodology

2.1 Model of the pipeline

The pipeline model is drawn in Solidwork software as shown in Figure 1. The length of the pipe is 2.5 meters, the nominal pipe size (NPS) is 0.152 meters, and the pipe measurement follows schedule 8.

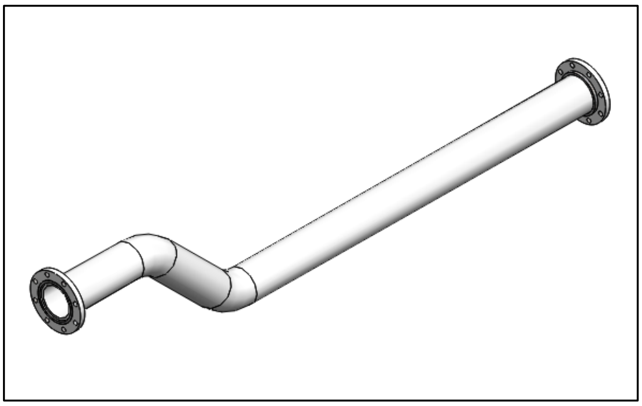

Figure 1: Isometric drawing of pipeline on Solidwork

2.2 Material

The material used for the pipeline is galvanized steel. Galvanized steel pipe is a carbon steel pipe coated with a zinc coating for protection. Table 1 shows the mechanical properties of the pipeline based on the ANSYS Workbench software.

Table 1: Mechanical properties

Material	Galvanized steel
Density	7850 $\mathrm{kg/m^3}$
Poisson's ratio	0.29
Young's Modulus	2.07E+11 Pa
Bulk modulus	1.6429E+11 Pa
Shear modulus	8.0233E+10 Pa
Yield strength	3.14E+08 Pa
Ultimate strength	5.02E+08 Pa

2.3 Modal Analysis

Modal analysis is the most basic sort of dynamic analysis, and it is responsible for determining the natural frequencies at which a structure will resonate. Modal analysis is a technique for determining a structural element's natural frequencies, mode shapes, and mode vectors. This analysis identifies the natural frequency of the pipeline and the mode shape of the pipeline for the different frequencies.

1) Condition 1- Free-free modal analysis
   In this analysis, no boundary condition will impose on the pipeline. The ANSYS settings were set for free modal analysis is shown in Table 2.

Table 2: ANSYS setting for free modal analysis

Object Name	Modal (A5)
State	Solved
Physics type	Structural
Analysis Type	Modal
Solver Target	Mechanical APDL
Environment Temperature	22℃
Generate Input Only	No

2) Condition 2 – With boundary condition
   For this analysis, the pipeline applies the boundary condition. The fixed support and the rotational velocity were set at the end of the pipeline. The rotational velocity that was used 2910 rpm. The rotational velocity of the centrifugal pump motor is 2910 rpm, which was obtained from the TECO manufacturer's catalog at the specification of the centrifugal pump. ANSYS settings for modal analysis with boundary conditions on the pipeline are shown in Table 3.

Table 3: ANSYS setting for free modal analysis

Object Name	Modal (B5)
State	Solved
Physics Type	Structural
Analysis Type	Modal
Solver Target	Mechanical APDL
Environment Temperature	22℃
Generate Input Only	No
Coriolis Effect	On

2.4 Harmonic Response Analysis

Harmonic Response Analysis is a type of linear dynamic analysis used to determine how a system responds to excitation at specific frequencies. It is also known as Frequency Response Analysis. Harmonic analysis shows that the peak response corresponds to its natural frequencies. The rotating force or torque from the centrifugal pump was 27.07 Nm and was applied to the flange pipe assembly, and the frequency response will be analyzed in this analysis. Table 4 showed the analysis settings used for harmonic response analysis.

Table 4: ANSYS setting for harmonic response

State	Fully Defined
Range Minimum	97.834 Hz
Range Maximum	953.85 Hz
Solution Intervals	10
Solution Method	Mode superposition
Cluster Result	No
Modal Frequency Range	Program controlled

5.5 Measurement of vibration

The six points are chosen for vibration measurement on the pipeline from the centrifugal pump. The reading was measured in both the horizontal and vertical directions of the pipeline. The equipment used for measuring the vibration on the pipeline is the vibration analyzer.

3. Results and Analysis

3.1 Modal Analysis

1) Condition 1- Free-free modal analysis
   This analysis aims to obtain the natural frequency for the pipeline without any boundary conditions. Table 5 shows the result of natural frequency and type of modes in condition 1, and Figure 2,3,4,5 shows the selected mode and contour of pipeline obtained from this analysis.

Table 5: Frequency and type of modes (Condition 1)

Mode	Frequency		Type of mode
	Hz	rad/s	
1	0	0	Rigid body displacement
2	5.2757e-004	0.003	Rigid body displacement
3	0	0	Rigid body displacement
4	0.49659	3.120	Rigid body displacement
5	0.5209	3.273	Rigid body displacement
6	2.1634	13.593	Torsion
7	81.499	512.073	Bending
8	116.82	734.002	Bending + Torsion
9	223.91	1406.868	Bending
10	226.85	1425.341	Bending + Torsion

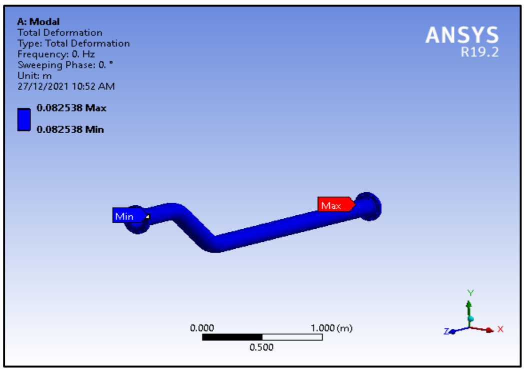

Figure 2: Mode shape 1 (0 Hz)

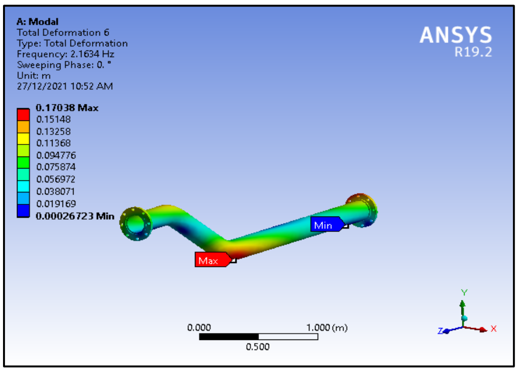

Figure 3: Mode shape 6 (2.1634)

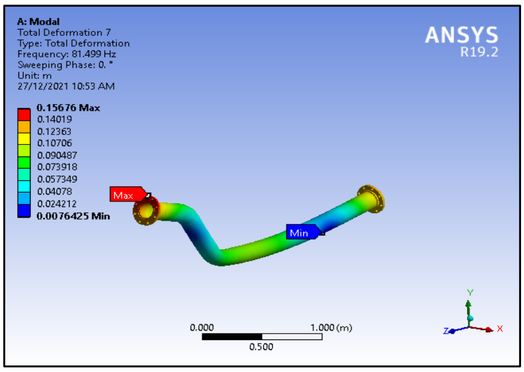

Figure 4: Mode shape 7 (81.499Hz)

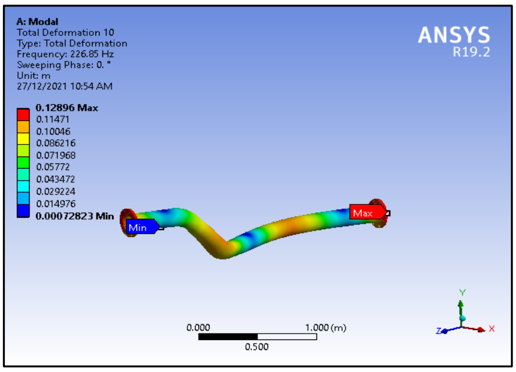

Figure 5: Mode shape 10 (226.85)

During natural free-frequency, the pipe should not vibrate. However, for some period of time, the pipeline vibrates because of its weight. The mode shape shows the contour of the pipeline at each frequency. The free natural frequency analysis shows that the minimum and maximum pipeline vibration are 0 Hz and 226.85 Hz, respectively. As a result of the analysis, the total deformation of the mode shape started to change at a frequency of 2.1634 Hz, and the maximum deformation at this frequency is 0.17038 m.

2) Condition 2 – With boundary condition

   The fixed support was applied at both flanges on the pipe, and the rotational velocity was set at 2910 rpm. The results of the natural frequency for condition 2 are shown in Table 6 and the selected natural frequencies and types of contours are shown in Figure 6,7,8 and 9.

Table 6: Frequency and type of modes (Condition 2)

Mode	Frequency		Type of mode
	Hz	rad/s	
1	97.348	611.656	Bending
2	160.55	1008.765	Bending
3	256.53	1611.826	Bending + Torsion
4	270.47	1699.413	Bending
5	429.03	2695.675	Bending + Torsion
6	534.03	3355.409	Bending
7	562.51	3534.355	Bending + Torsion
8	632.18	3972.104	Bending
9	750.48	4715.405	Bending + Torsion
10	953.85	5993.216	Bending

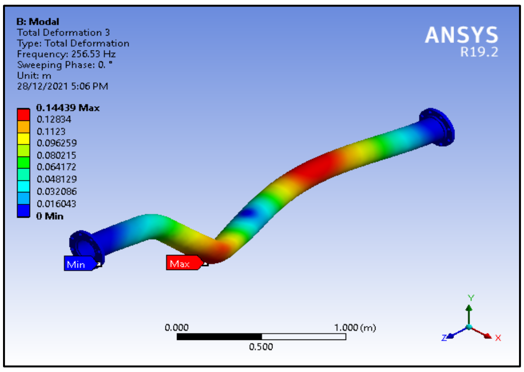

Figure 6: Mode shape 3 (256.53 Hz)

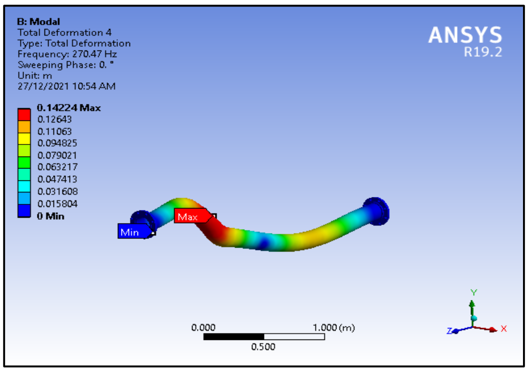

Figure 7: Mode shape 4 (270.47 Hz)

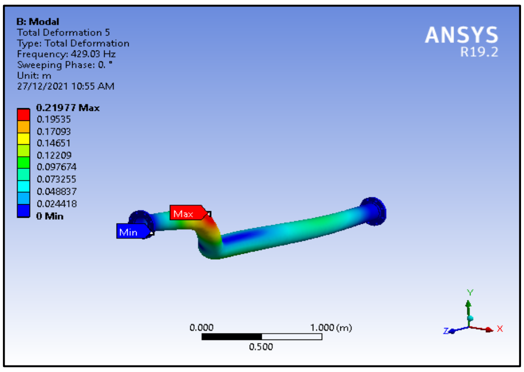

Figure 8: Mode shape 5 (429.03 Hz)

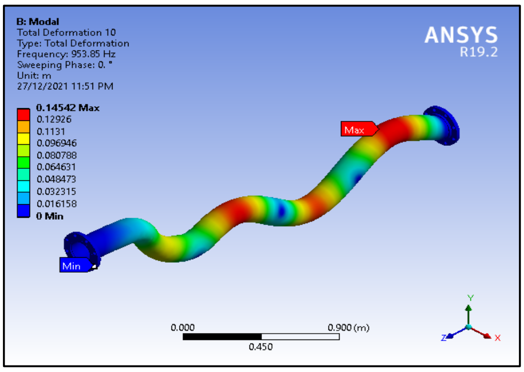

Figure 9: Mode shape 10 (953.85 Hz)

Ten natural frequencies were obtained through the modal analysis of the pipeline, and the minimum and maximum natural frequencies after applying the boundary condition were different from the free natural frequency in condition one. The minimum and maximum natural frequencies were 97.348 Hz and 953.85 Hz, respectively. At a different frequency, it shows different behavior. The pipeline starts bending at the natural frequency of 97.348 Hz. From Figure 6, when the natural frequency was 256.53 Hz, the deformation of the pipeline started bending and torsion, and the maximum total deformation was 0.14439 m. Figure 9 shows the total deformation of the pipeline was bending at the maximum natural frequency (953.86 Hz) of the pipeline. The maximum deformation at this frequency was 0.14542 m.

3.2 Harmonic Response Analysis

The minimum and maximum natural frequencies obtained from the modal analysis for condition two were used in the harmonic response analysis to determine the frequency response for deformation, velocity, and acceleration. The harmonic response analysis also shows the total velocity of the pipeline. The result was explained based on the graph obtained from the harmonic response analysis. This analysis obtained three graphs, and there was deformation, velocity, and acceleration. Figures 10, 11 and 12 showed the graph of amplitude variation with different exciting frequencies for deformation, velocity and acceleration, respectively.

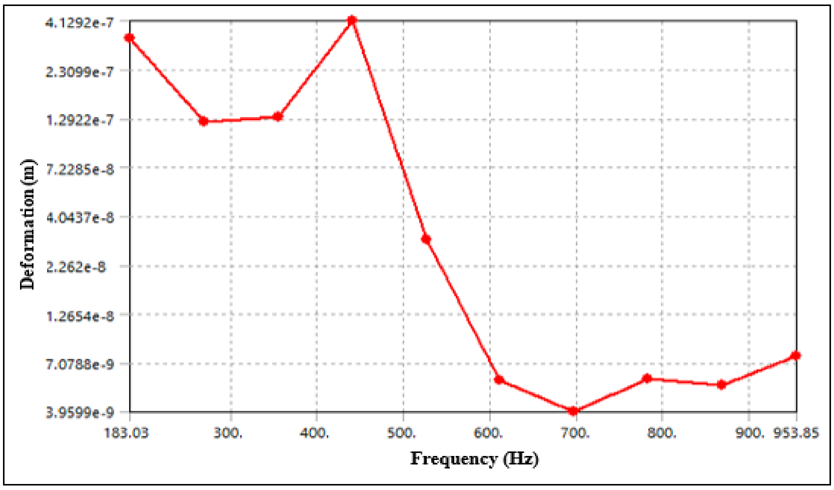

Figure 10: Variation of displacement amplitude with different exciting frequencies

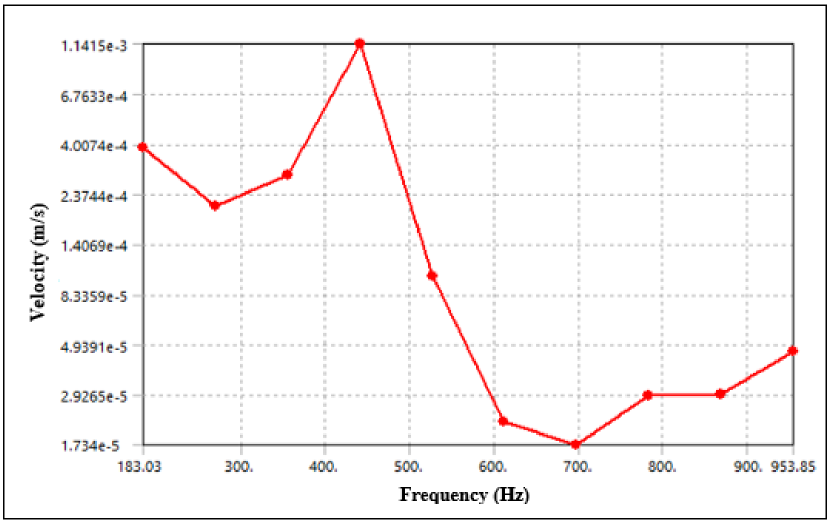

Figure 11: Variation of velocity amplitude with different exciting frequencies

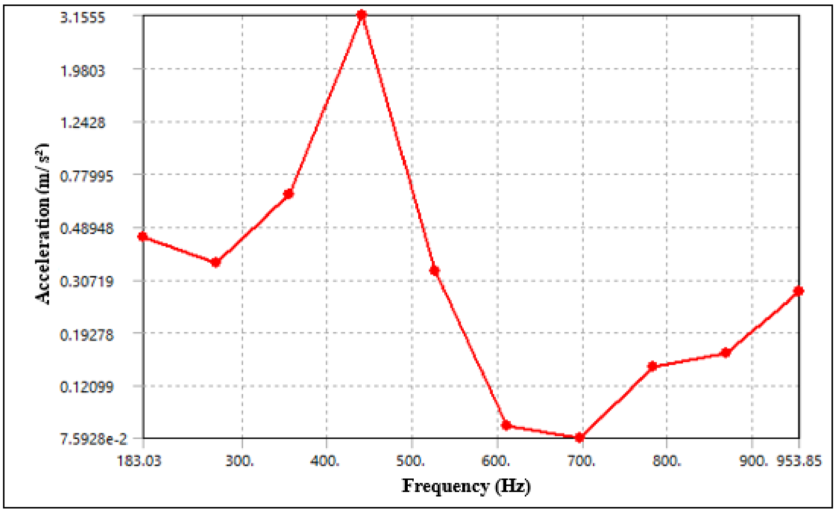

Figure 12: Variation of acceleration amplitude with different exciting frequencies

From the graph obtained, the frequency response for deformation, velocity, and acceleration was the peak response corresponding to the structure's natural frequencies in the resonant condition when the corresponding load frequencies matched the pipe's natural frequency. Based on the peak amplitude obtained, it can predict the behavior of a pipe under vibration and check out the pipe's critical frequencies. From the peak of deformation, velocity, and acceleration, it can be seen that the critical frequency is 439.97 Hz when it shows the maximum peaks of amplitude. The maximum deformation, velocity, and acceleration frequency response peaks are 4.1297m, 1.1415 m/s, and 3.1555, respectively.

Based on the result of maximum amplitude obtained, the amplitude limit can be reduced by reducing the frequency based on the average frequency from the previous result. This is to avoid the effect of high amplitude on the design of the pipeline. Therefore, the frequency was set from 0-568 Hz. The graph in figure 13, 14 and 15 below shows the maximum peak amplitude of deformation, velocity, and acceleration when changing the frequency.

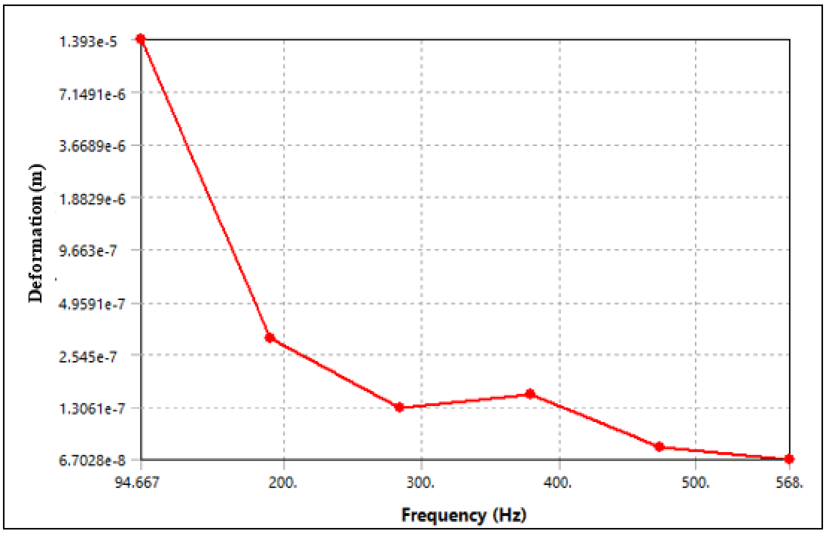

Figure 13: Variation of deformation amplitude with different exciting frequencies (0-568 Hz)

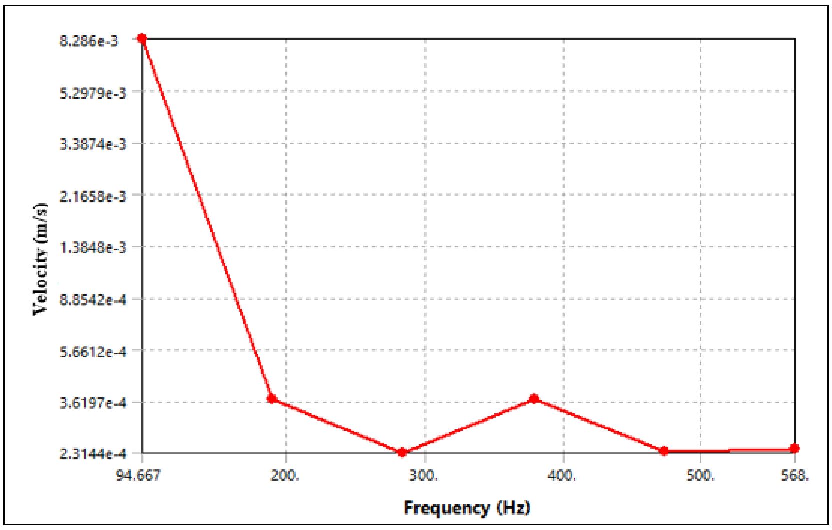

Figure 14: Variation of velocity amplitude with different exciting frequencies (0-568 Hz)

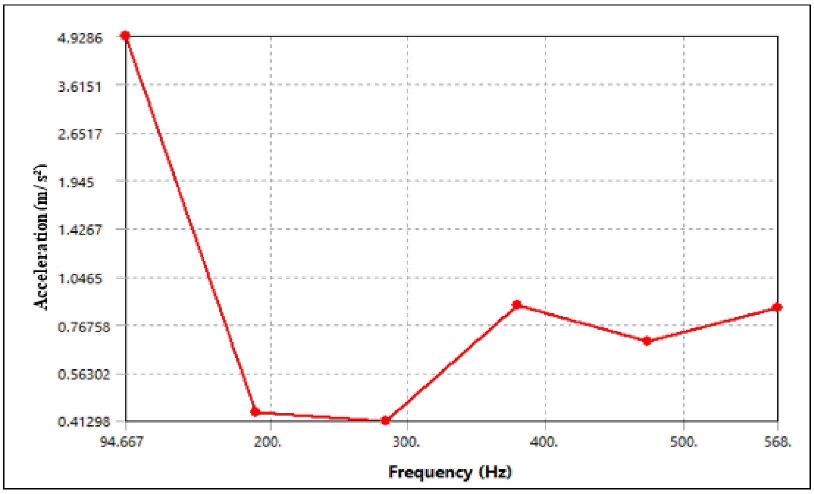

Figure 15: Variation of acceleration amplitude with different exciting frequencies (0-568 Hz)

From the graph amplitude with frequency obtained from the analysis, when changing the frequency to 0–568 Hz, the maximum peak response obtained is 94.667 Hz for deformation, velocity, and acceleration. So, this frequency was the maximum response for deformation, velocity, and acceleration. Therefore, this maximum peak response must be reduced or eliminated to avoid the destructive effect on the pipeline.

3.3 Total velocity

The maximum and minimum velocity for the pipeline at each frequency was shown in the total velocity result. These are a few of the 10-set frequencies that were extracted.

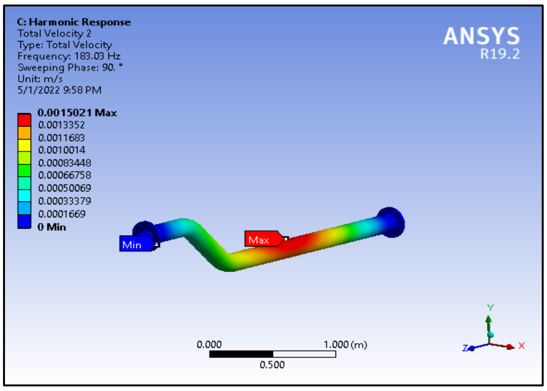

Figure 16: Total velocity at 183.03 Hz

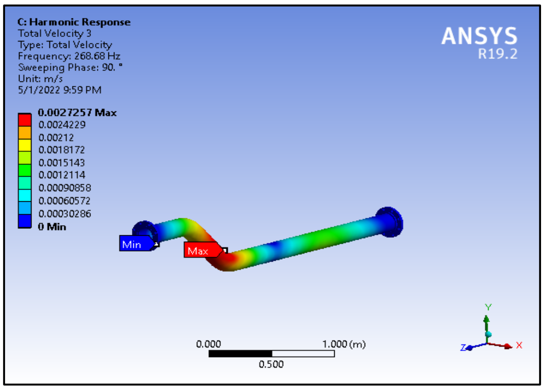

Figure 17: Total velocity at 268.68 Hz

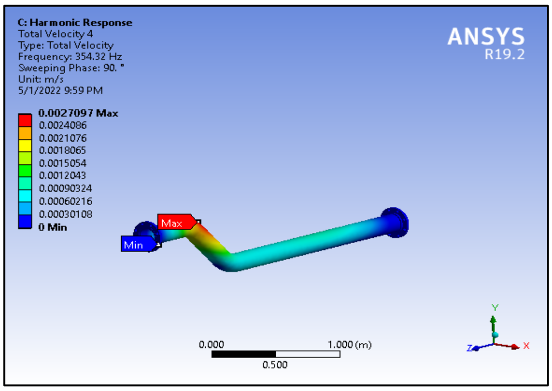

Figure 18: Total velocity at 354.32 Hz

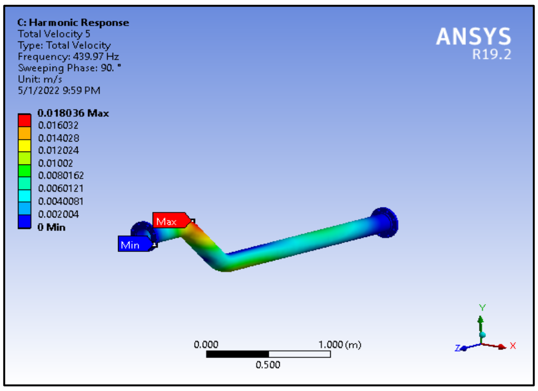

Figure 19: Total velocity at 439.97 Hz

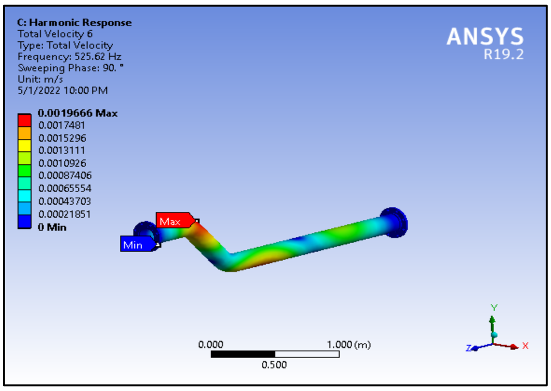

Figure 20: Total velocity at 535.62 Hz

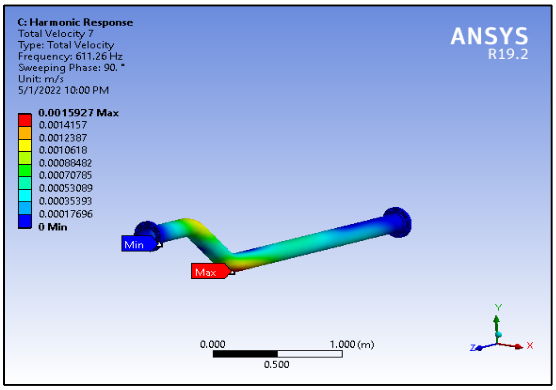

Figure 21: Total velocity at 611.26 Hz

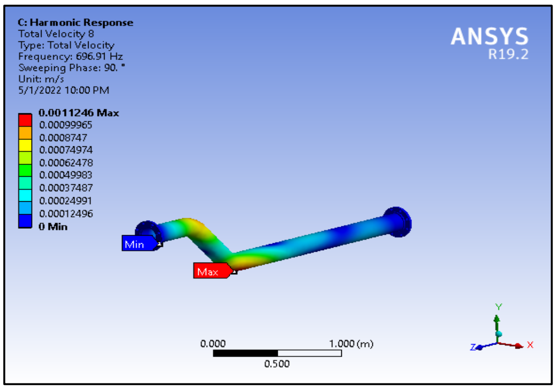

Figure 22: Total velocity at 696.91 Hz

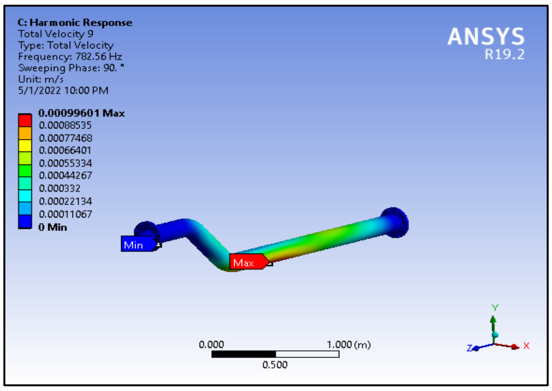

Figure 23: Total velocity at 782.56 Hz

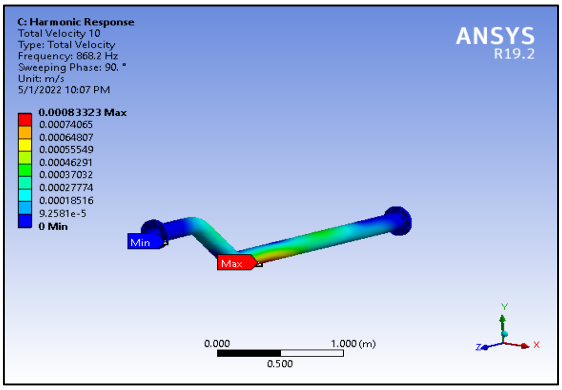

Figure 24: Total velocity at 868.2 Hz

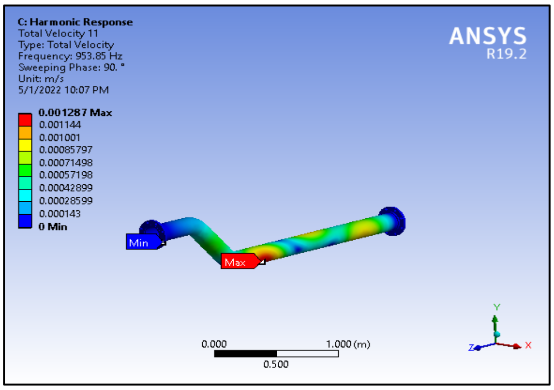

Figure 25: Total velocity at 953.85 Hz

Based on the result obtained, the maximum and minimum velocity on the pipeline for each frequency can be analyzed. From the total velocity result analysis, it can be observed that the highest maximum velocity was at the frequency of 268.68 Hz, followed by 354.32 Hz, and the maximum velocity was 0.002725 m/s and 0.027097 m/s, respectively. Therefore, at the different frequencies, it shows the different maximum velocity points of the pipeline. That means the maximum total velocity depends on frequency and design of the pipeline.

3.4 Measurement Result

The measurement of vibration was measured in velocity and in the horizontal and vertical directions. Six points of vibration were taken for the measurement. As seen in Table 7, the velocity of vibration for horizontal and vertical points has different values for each measurement point. The measurement point starts from the pipe at the cooling tower until the centrifugal pump. The effect of the rotating force from the centrifugal pump causes the vibration on the pipeline, so the measurement of this velocity was to identify the vibration on the pipeline. Based on the measurements obtained, the horizontal velocity from measurement points one to five increased, and it decreased at point six. The closer the pipeline to the centrifugal pump, the higher the vibration. The value of point six is lower because the joint between the pipe and the centrifugal pump was strong and can reduce the effect of vibration on that part of the pipeline. Therefore, the measurement velocity on the horizontal is higher than the vertical value. That means the vibration produces at horizontal direction is higher than the vertical direction from the centrifugal pump. At point five, the horizontal and vertical velocity was higher than at another point. This was because, at point five, the bellow pipe was installed, and it can absorb vibration from the pipeline.

Table 7: Measurement of vibration velocity

Point	Vibration reading			
	Position			
	Horizontal		Vertical	
	mm/s	m/s	mm/s	m/s
1	2.39	0.00239	2.09	0.00209
2	3.59	0.00359	2.03	0.00203
3	4.14	0.00414	1.41	0.00141
4	6.18	0.00618	2.31	0.00231
5	9.30	0.00930	6.53	0.00653
6	2.75	0.00275	2.12	0.00212

3.5 Comparison of Simulation with Measurement Results

There is a large difference in the velocity result between the simulation and the vibration measurement experiment on the pipeline. Simulation is the numerical model used to generate natural frequency data and frequency response for deformation, velocity and acceleration. Simulation result shows a very high precision value, that is around 1.1415×10^{-3} till 4.5814×10^{-5} m/s. While in experiment the precision value low that is around 1.41×10^{-3} till 9.3×10^{-3} m/s. From the experimental reading, was found that the speed of 0.00141 m/s is equivalent to the reading in the simulation of 0.00114 m/s and can be considered to have vibrated on the pipeline. The simulation results represent the behaviour of the pipeline based on its theoretical model. However, the vibration measurement result represents the actual behaviour of the pipeline under the effect of vibration from a centrifugal pump. The measurement result is based on a real-time system when vibration occurs on the pipeline. Therefore, the measurement result gives more accurate results when compared to the result obtained from the simulation. The simulation result help us to be more critical when the occurrence of vibration on the pipeline can be prevented earlier.

4. Conclusion

From the result of the simulation on modal analysis, we can identify the minimum and maximum natural frequencies of the pipeline with and without any boundary condition. Deformation of the pipeline was observed based on the mode shape for each frequency. Based on the result of modal analysis, the minimum natural frequency of the pipeline shows the mode shape start bending at 97.348 Hz. It can be concluded that to avoid pipeline damage, the frequency suitable for the pipeline must be lower than 97.348 Hz. The different frequencies show the different behaviour of deformations on the pipeline. The harmonic response of the pipeline to the excitation is in the range of 97.834 Hz to 953.85 Hz. The frequency response, which is the variation of displacement, velocity, and acceleration amplitude with respect to frequency, has been graphically plotted. Based on the result of the graph obtained from the harmonic analysis, the maximum peaks of deformation, velocity, and acceleration of the pipeline can be seen at the same frequency. So, the critical frequency is 439.97 Hz. That means we must avoid this frequency to prevent damage to the pipelines. The total velocity of the pipeline has also been studied. The different frequencies show the different maximum velocity points of the pipe.

In addition, from the measurement of vibration by using the vibration analyzer, the measuring data was recorded for horizontal and vertical direction. The horizontal direction measurement shows the higher reading of velocity compared to the vertical direction. In conclusion, the vibration in the horizontal direction is higher than in the vertical direction.

As for the recommendation, the future researcher can add calculations to ensure that the result obtained is accurate, and this can be done with the support of vibration measurement to be used in industrial applications. Moreover, next researcher can involve more parts of the pipeline at rotating equipment based on the different rotational forces from the rotating equipment to make sure that the highest of pipe vibration can be found along the pipeline at the UTHM plant biodiesel. Last but not least, for the future researchers, the flow of fluid would be considered to compare the vibration occurs highest from rotating equipment or flow in the pipeline. The fluid flow also affecting the vibration on the pipeline.

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