Study on Water Hammer Effect in Turbulent Flow through the Pipe System

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ARTICLE INFO	ABSTRACT
	The purpose of this research is to study water hammer effect in turbulent flow through the pipe system. The water hammer occurs when the water flow in the pipeline is suddenly stopped by the valve. Water hammer can cause the pipe to break if the pressure is high enough. An experimental method has been conducted to investigate the effect of design parameters such as difference kind of material properties of pipes and the effect of the flow rate of fluid on the frequency (Hz) and the maximum acceleration of vibration signal (m/s²) during water hammer effect, the vibration signal is captured by using the DEWE-41-T-DSA signal analysis and piezoelectric accelerometer sensor. Data signal is transferred to DEWESoft software to be analyzed using the Fast Fourier Transform (FFT) method. We found that the maximum acceleration vibration signal will increase the flow rate of fluid increase. Besides, the maximum acceleration vibration signal of UPVC pipe is higher than HDPE pipe. Meanwhile, for the frequency, the experimental result shows that the larger frequency is the UPVC pipe compare with the HDPE pipe. This is due to the compressibility of fluid and elasticity of the pipe. Therefore, it can be concluded that the UPVC pipe deal with more water hammer effect compares to the HDPE pipe due to the mechanical properties difference of UPVC and HDPE pipe.

1. Introduction

Now days in our life, the water hammer phenomena are almost happening every day at home or even in the industry that includes the piping system and people don't see it [1]. The water hammer generally fluid hammer that we can detect it at home when somebody simply turning off a shower quickly [2]. It familiar nearly everyone who feel the vibration and heard a loud thud like 'knock' through the mansion. The phenomena of water hammer also happen in industrial field such as power steam plant were commonly had use steam and water in their piping system [3,4]. Alike in the oil and gas company, such Petronas Company is the company had used steam as the power to move the

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plant and pipe to transfer the oil. Therefore, the engineer needs to be creative and problem solver to prevent the water hammer phenomena keep happen [5].
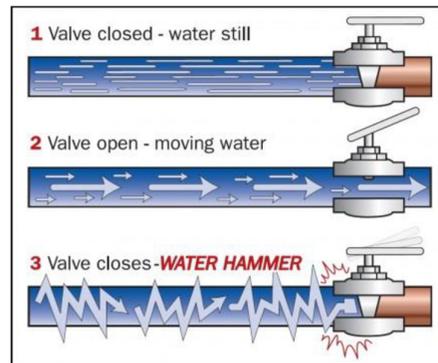

Fig. 1. Analogy water hammer [1]

Due of the water hammer happen creating some issue that causes the piping system. The issue piping system in the industry will have a severe accident and a big loss that could occur if there are any prevention or precaution is not taken by the company. If may damage the equipment such as pipe failure, the breakdown of a pump system, the rapture of valve and ruin product [6,7]. The water hammer can cause the piping line to break if the pressure high enough. Water hammer is a low frequency phenomena that happen in a pipe that has water flow. This phenomena is caused by the changing of momentum and the pressure of sudden wrote in closure pipe [8]. The changing of momentum will result from the pressure wave traveling around the entire pipe and 2 volunteered with certain of speed until it stops when the loss of staff occurred gradually [9].

The major problem of issues that related to the water hammer effect is the vibration in flow pipe and equipment. The vibration effect from water hammer in pipeline system can cause damage there is fatigue to the pipe material because of the vibration occurs almost every days [6]. There are some major categories of piping vibration and several vibration types each category. The major categories are steady-state and transient [10].

The steady-state vibration of pipe can be delineated as a repetitive vibration that takes place for a relatively long time period. It is caused by a time-varying force acting along the pipe. The force may generate by rotating or reciprocating equipment by means of vibration of the equipment itself or as a result of the fluid pressure pulses [11]. The fatigue failure in pipe flow is caused by the excessive steady-state vibration due to a large number of high-stress cycles and this failure always occur at stress concentration points such as branch connection, threaded connection, fillet weld and elbow. Steady-state vibration happen either low frequency or frequency (300 > Hz > 300). The low frequency can cause lateral displacement of the pipe while the higher frequency can be flexural vibration of the pipe wall itself in addition to lateral pipe movement [12].

Piping transient vibration that occurs for a relatively short period of time and is usually caused by larger exciting forces differing from the steady-state vibration. In piping, the primary cause of dynamic transients is a high or low pressure pulse traveling through the fluid [1,3,4]. Pressure pulses traveling through the fluid are most common cause of transient vibration in the piping system. The pulse can result in large forces acting in the axial direction of the piping, the magnitude of which is normally proportional to the length of the pipe leg. The longer the pipe leg, the larger the dynamic transient force the piping wall experience. A common transient piping vibration is water hammer that may be caused by rapid pump start or stop or by quick valve closing or opening [13].

The main objective of this project is to study the compare effect between elastic and rigid pipe with the turbulent of water flow rate of the natural frequency and acceleration vibration signal. The impact force produced causes the fluid adjacent to the valve compressed and the vibration inside the pipeline increase. The repetition of this process within a period of time increase the probability of the piping system to fail and fracture [14]. Finally, the research of an experiment is conducted to study the vibration effect on the rigid and elastic pipe when the valve is suddenly closed under the condition of water hammer. This experiment is conducted to study whether the rigid and elastic pipe influent the effect of water hammer effect [15].

2. Methodology
2.1 Material

Initially the detailed parameters, size and material of actual design such as average diameter pipe, pipe thickness, and pipe material are determined. The material selection of the pipe, namely pipes Poly Vinyl Chloride (PVC), galvanized iron pipes (BG) and poly pipe High Density Polyethylene (HDPE). The experiment use pipe system will be modelled according to the experimental setup. For this experimental method, it had been decided to compare the result that the material used for the pipe system, the rigid pipe is unplasticized polyvinyl chloride (U-PVC) and the elastic pipe is High Density Polyethylene (HDPE). Table 1 and 2 show the material and metallurgical characteristics of UPVC BS 3505 Class D pipe and HDPE Material Grade PE 80 pipe [16, 17].

Fig. 2. Pipe of UPVC BS 3505 Class D [16]

Table 1
The Characteristics of UPVC BS 3505 Class D Pipe [16]

Item	Specification
Specific gravity	1.40-1.43 g/cm^2
Specific heat	0.25 Kcal/kg/°C
Thermal conductivity	0.13 Kcal.Cm. H°C
Tensile strength	500 kg/cm^2
Elongation	80%
Modulus elasticity	1200-1500 MPa
Hardness-shore D	85-90
Flammability	Self-Extinguishing

Fig. 3. Pipe of HDPE Material Grade PE 80 [17]

Table 2
The Characteristics of HDPE Material Grade PE 80 [17]

Item	Specification
Specific gravity	0.93-0.97 g/cm^2
Heat conductivity	0.43 W/mk
Modulus of elasticity	800 MPa
Tensile yield strength	20 Mpa
Elongation	10%
Modulus elasticity	1200-1500 MPa
Hardness-shore D	59
Flammability	Self-Extinguishing

Fresh water is used for the fluid test in the experiment density to 1000 kg/m³. The bulk modulus is 2.19 x 109 Pa and other properties are shown in Table 3.

Table 3
The properties of fluid with standard pressure atmosphere [4]

Liquid	Temperature (°C)	Density, ρ (kg/m³)	Bulk Modulus. K (GPa)
Benzene	15	880	1.05
Ethyl Alcohol	0	790	1.32
Glycerin	15	1260	4.43
Kerosene	20	804	1.32
Mercury	20	13570	26.2
Fresh Water	20	999	2.19
Oil	15	900	1.5

2.2 Experimental Setup

An experiment is set up as shown in the diagram, Figure 4 to analysis the vibration test with the variation of velocity with turbulent flow. The parameter used for the experiment has set up which consist the dimension of the pipe such as the diameter, the thickness, material of the pipe and the length of the pipe. The pipe will be installed in the tested area. The vibration sensor using the piezoelectric accelerometer sensor is placed at the end of the modal tested pipe.
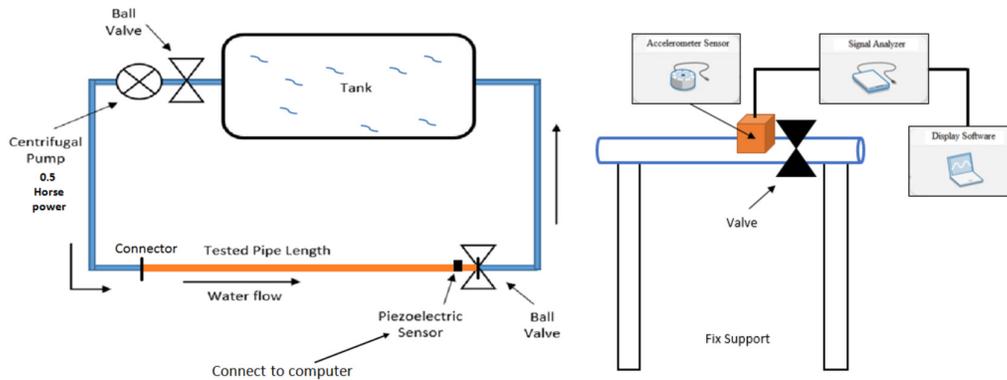
Fig. 4. Schematic Diagram [3]

This sensor is used to measure the vibration response of the tested area. The model of the accelerometer is the Kistler accelerometer type 8640A50 that shows in Figure 4 that has higher stability, wider frequency, and dynamic range compares to others. It's also can be used for this testing is a high sensitivity single axis accelerometer.

2.3 Experimental Procedure

I.   The accelerometer was connected to signal analyser with cable ICP, while the USB connector of the signal analyser is connected to the computer by running on the DEWESoft software.
II. The ICP cable is connected to the analog 0 (A0).
III. DEWESoft software is running on the monitor, then every channel connection is set up according to the units of measurement, measurement range and sensitivity of the sensor.
IV. The sensitivity of the sensor is set up to 0.01 V/ms-2.
V.   The piezoelectric accelerometer sensor is mounted on the surface of the pipe beside the ball valve that controls the on/off process using the wax.
VI. The centrifugal pump is switched on to circulate the water flow in the pipe system. The first experiment is used the rigid of a pipe.
VII. The valve that controls the speed of the water is adjusted to full, three quarter and half.
VIII. All the data of vibration response such as RMS value, amplitude, FFT frequency are recorded.
IX. Repeat again step VI and VII by using the other materials of pipe, which is elastic pipe

3. Results and Discussion
3.1 Specification Test

Theoretically, analytical calculation a part of an analysis of research. There are several specification tests for the parameters that need to calculate before to running the experiment which is Flow rate, velocity and Reynolds number.

3.1.1 Flow rate

Generally, the flow rate is the volume of fluid which passes per unit time. In the experiment, there are three different of flow rate which are flow rate 1 (Q_1), flow rate 2 (Q_2) and flow rate 3 (Q_3). Therefore, to make a variety velocities, the first valve on the centrifugal pump was adjusted to fully open, three-quarter open and half open. There are also have 2 different type of pipe.

Table 4
Result of Flow Rate in Rigid Pipe

Open Valve	Fluid liter, L/1000, m^3	Time, s	Flow rate, Q, m^3/s	Average, m^3/s
Full (Q3)	0.015	28.57	5.2503×10^{-4}	5.2512×10^{-4}
		28.85	5.1993×10^{-4}	
		28.28	5.3041×10^{-4}	
Three-quarter (Q2)	0.015	29.30	5.1195×10^{-4}	5.1035×10^{-4}
		29.20	5.1370×10^{-4}	
		26.68	5.0539×10^{-4}	
Half (Q1)	0.015	30.48	4.9213×10^{-4}	4.8989×10^{-4}
		30.81	4.8685×10^{-4}	
		30.57	4.9068×10^{-4}	

Table 5
Result of Flow Rate in Elastic Pipe

Open Valve	Fluid liter, L/1000, m^3	Time, s	Flow rate, Q, m^3/s	Average, m^3/s
Full (Q3)	0.015	29.27	5.1247×10^{-4}	5.0957×10^{-4}
		29.16	5.1440×10^{-4}	
		29.89	5.0184×10^{-4}	
Three-quarter (Q2)	0.015	30.23	4.9620×10^{-4}	4.9188×10^{-4}
		30.78	4.8732×10^{-4}	
		30.48	4.9213×10^{-4}	
Half (Q1)	0.015	33.67	4.4550×10^{-4}	4.4564×10^{-4}
		33.83	4.4339×10^{-4}	
		33.48	4.4803×10^{-4}	

From the both of table of flow rate in the pipes. The result of flow rate that Q_3 is larger flow rate than Q_1 and Q_2. Hence, Q_3 have a fully open valve that why the water can though a lot in pipes.

3.1.2 Velocity

The flow velocity of the experiment in both pipes has not differed much. It in range 1.42-1.67 m/s.

Table 6
UPVC, Rigid pipe

bv	Flow Rate, Q m^3/s	Area, A, mm^2	Velocity, m/s
Q_1	4.9898×10^{-4}		1.59
Q_2	5.1035×10^{-4}	3.1416×10^{-4}	1.62
Q_3	5.2512×10^{-4}		1.67

Table 7
HDPE, Elastic Pipe

Parameter	Flow Rate, Q m^3/s	Area, A, mm^2	Velocity, m/s
Q_1	4.4564×10^{-4}		1.42
Q_2	4.9188×10^{-4}	3.1416×10^{-4}	1.57
Q_3	5.0957×10^{-4}		1.62

3.1.3 Time domain analysis

In the time domain, the signal or function's value is known for all real numbers, for the case of continuous time, or at various separate instants in the case of discrete time. An oscilloscope is a tool

commonly used to visualize real-world signals in the time domain. A time domain graph shows how a maximum acceleration of vibration changes with time. Therefore, the result of the maximum acceleration of vibration can be determined by two parameters [18,19]. One is the relationship between maximum acceleration vibrations with a variety of water flow rate. Second is the relationship of maximum acceleration vibrations with the different pipe of type. Table 8 shows the tabulation data for maximum acceleration vibration with two parameters.

Table 8
Tabulation Data for Maximum Acceleration Vibration with Parameters

Parameter		Max Acceleration, a (m/s^2)
Type of pipes	Flow rate	
UPVC (Rigid)	Q_1	93.45
	Q_2	99.20
	Q_3	101.78
HDPE (Elastic)	Q_1	50.23
	Q_2	55.98
	Q_3	61.72

(a) Rigid pipe at Q_1

(b) Rigid pipe at Q_2

(c) Rigid pipe at Q_3

(d) Elastic pipe at Q_1

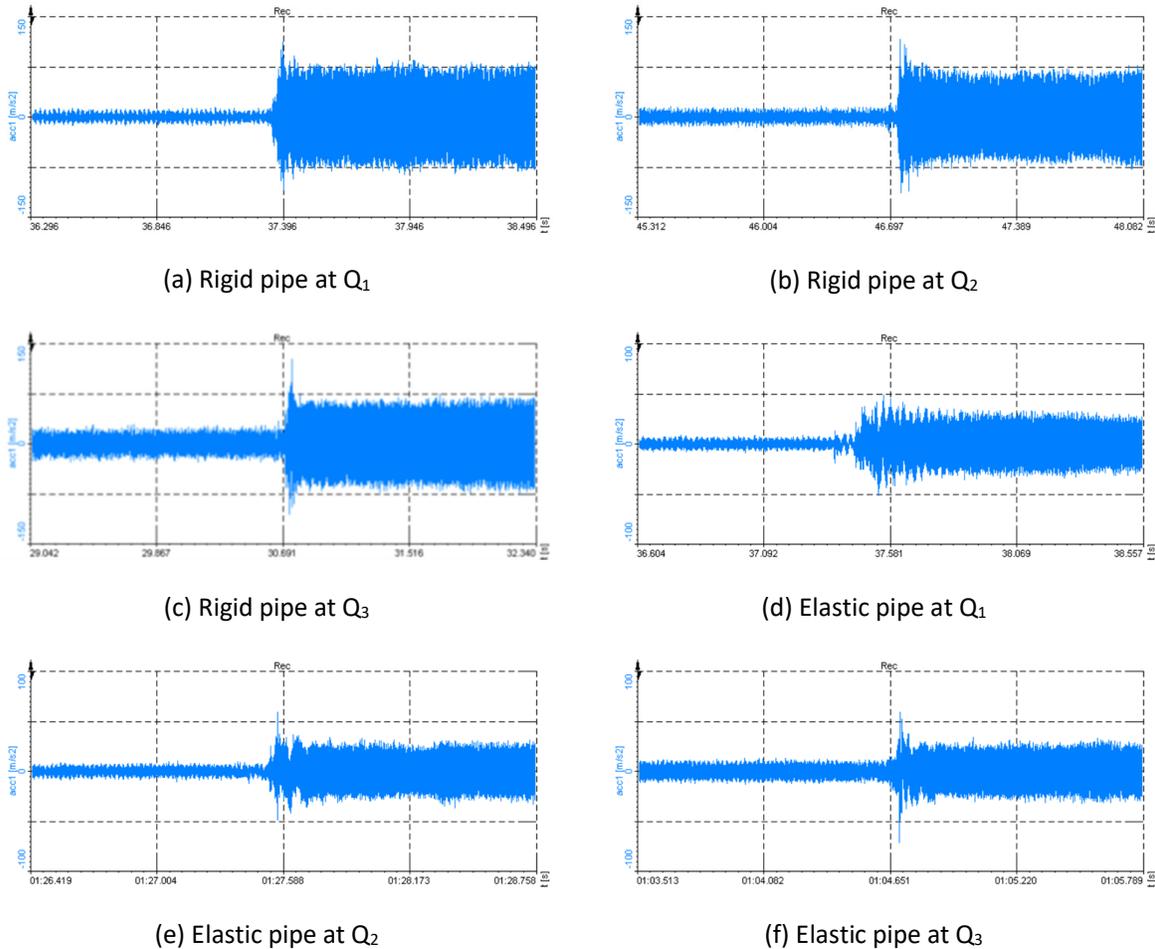(e) Elastic pipe at Q_2

(f) Elastic pipe at Q_3

Fig. 5. Max acceleration

The data above showed is the maximum average acceleration of two type of pipe. The data of maximum average acceleration a, m/s^2 was taken for simulation of Dewesoft. During the experiment, the simulation shows the result of maximum average acceleration. The Dewesoft give the data as shown in Figure 5 (a)-(f). The data is by graphical which maximum average acceleration versus time.

Based on the Figure 5 show the changes of maximum average acceleration before, after and during water hammer in flow rate Q_1, Q_2, and Q_3 between of elastic and rigid pipe. The change of maximum average acceleration is formed from different of flow rate Q_1, Q_2, and Q_3. Besides that, type of pipes also may affect the maximum average acceleration. From Figure 5 is interpreted into simple graph Figure 6 and Figure 7 that combine all flow rate. By used Root Mean Square (RMS) data analysis which is an average positive value that converted by the amplitude signal. The amplitude signal gives positive and negative values, so it is difficult to detect where the time of exactly water hammer occurs after the valve is suddenly closed.

Both Figure 6 and Figure 7 show the graph of maximum average acceleration versus the time of water by the flow rate Q_1, Q_2, and Q_3. The peak acceleration value shows the condition of the water hammer phenomena happen in an experiment using rigid pipe and experiment using the elastic pipe. It seems that the maximum acceleration occurs at a flow rate at Q_3 is higher compared to the others flow rate which followed by the Q_1 and Q_2. The acceleration vibration is increase as the water flow rate increase. This is due by the pressure wave of collision between the pressure waves reverse with the pressure wave forth has reduced the shock wave [1]. According to a study by Nurul Hidayah [6], she proved that the RPM of the pump lower will decrease the amplitude of the vibration signal. The high water impact occurs when the speed of the water flow rate is larger when the suddenly closed valve.
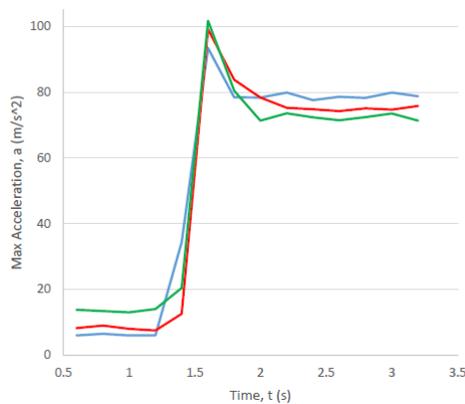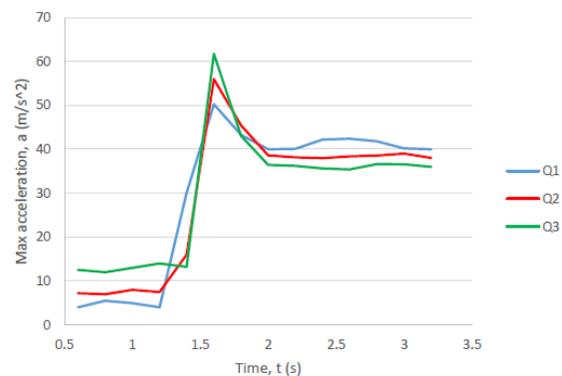

Fig. 6. Max acceleration Rigid Pipe

Fig. 7. Max acceleration Elastic Pipe

While after the water hammer occurred the maximum acceleration it seems contrast. The Q_1 is higher than to the Q_2 and Q_3 in both pipes. This may due to the pressure impact during water hammer is resisting the flow of the water. The reflection of the water hammer is made impaction of the valve to be reduced [8]. If high maximum acceleration during water is mean low maximum acceleration after water hammer.

3.1.4 Frequency domain analysis before water hammer

To analysis water hammer more details, there need to see the condition before water hammer occur. In water hammer phenomena usually, the data before water hammer happen is also important that want sees and compare from the data during the water hammer occur. The condition before the

water hammer can be determined by referring to the frequency spectrum that appears from the FFT data signal graph. This data also was analyzed by using Dewesoft software 8 shows only the frequency reading for different pipe type in rigid and elastic and different of water flow rate.

According to Figure 8, the graph illustrates the dominant frequency for condition before the water hammer phenomena from DeweSoft software. The condition water flow inside the pipe flow is a constant flow. This discussion is want to see the result of the relationship of natural frequency before the water hammer with two parameters which is the different pipe parameter and a variety of water flow rate. The result of frequency is between the pipes which are rigid and elastic and the flow rate which is Q_1, Q_2, and Q_3.
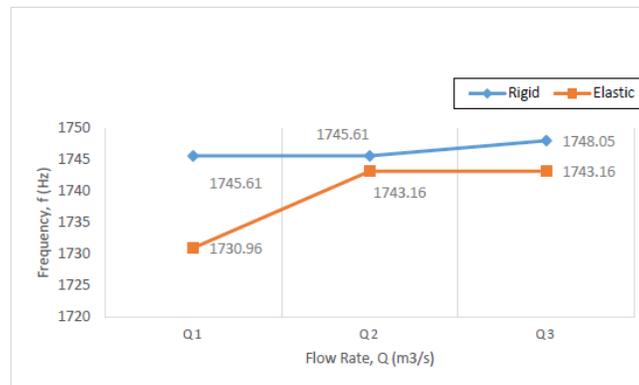

Fig. 8. Condition Frequency before Water Hammer

From the result, it can explain that the natural frequency before the water hammer condition can be valued in the range of 1730 Hz to 1750 Hz. This condition is the normal condition where only the normal flow of water without any obstacle that disrupt. In other words that range value shows the natural frequency appear. The value is not very consistent maybe due to the technical error while doing the experiment, but the pattern natural frequency still can be used to know the condition before the valve closed suddenly [11].

3.1.5 Frequency domain analysis during water hammer

The condition during the water hammer phenomena can be determine using the same procedure as before the water hammer phenomena. Nevertheless, the difference is during water hammer is there is a sudden closure of the valve where is a flow rate of water in the pipe and only can be analyzed by looking for the pattern natural frequency at FFT frequency spectrum shown below.

Figure 9 (a)-(f) are the graph pattern of the frequency spectrum that shows the condition during the water hammer impact. From the graph, it can be analyzed that the graph shows the peak frequency is changing due to the impact of the water at the pipe after the valve is suddenly closed. Each graph for each experiment shown different of the pattern because of different pipe diameter with a variety of water flow rate. At this moment, the water condition in the turbulent flow region, where the water flow hit the valve and turn back the opposite direction and water that continue flowing from the suction pump hits the opposite direction and this phenomena called the hydraulic shock wave [5].
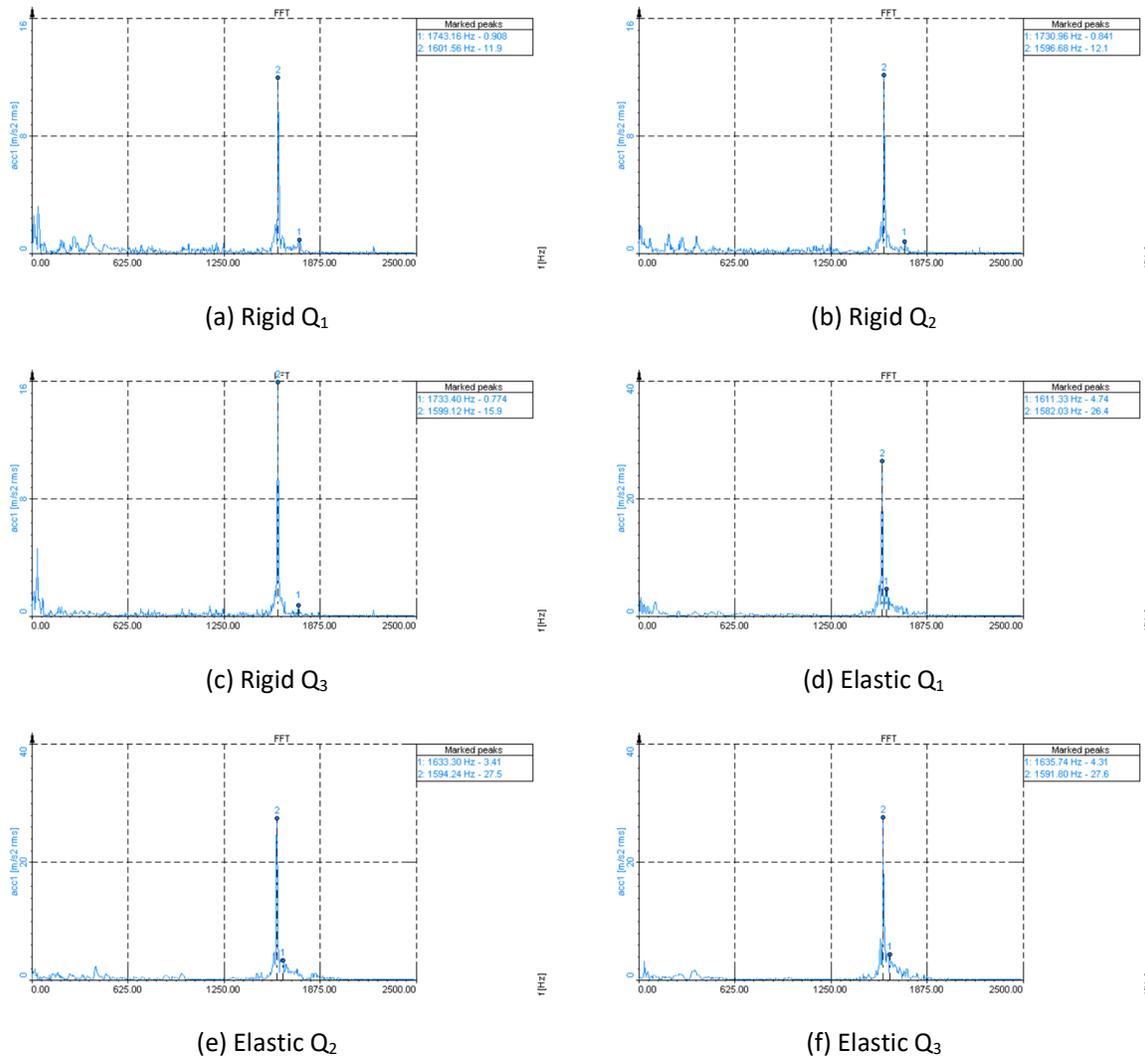
(a) Rigid Q_1

(b) Rigid Q_2

(c) Rigid Q_3

(d) Elastic Q_1

(e) Elastic Q_2

(f) Elastic Q_3

Fig. 9. FFT Frequency Spectrum

As a result, the trend of difference between peak 1 and peak 2 is same, where the flow rate of the fluid is increase than the difference of frequency also increase. However, the changing of the frequency of peak of rigid pipe is larger than elastic pipe which is approximately three-fold of value elastic pipe. So rigid pipe is more effect of water hammer compare to the elastic pipe. The non-rigid pipe can absorb the strain energy and reduce the speed of the pressure wave during the water hammer phenomena. This is proved by Parmakian [9] that the more rigid the pipe wall is, and the higher the water hammer pressure will be [9].

3.1.6 Frequency domain analysis after water hammer

To analysis water hammer more details, there need to see the condition after water hammer occur too. In water hammer phenomena usually, the data after water hammer happen is also important that want sees and compare the data during the water hammer occur. The condition for after water hammer it can see in perspective of the safety of the pipeline system. For the example what the effect when the valve is continuous closed. The condition after the water hammer can be

determined by referring to the frequency spectrum that appears from the FFT data signal graph. This data also was analyzed by using Dewesoft software.

According to the Figure 10, the graph illustrates the dominant frequency for the condition after the water hammer phenomena from DeweSoft software through FFT frequency spectrum. The condition water flow inside the pipe flow is a constant flow. This discussion is want to see the result of the relationship of natural frequency after the water hammer with two parameters which are the different pipe parameter and a variety of water flow rate that the process where the valve is closed and the water flow keeps continue hitting the valve. The result of frequency is between the pipes which are rigid and elastic and the flow rate which is Q_1, Q_2, and Q_3.
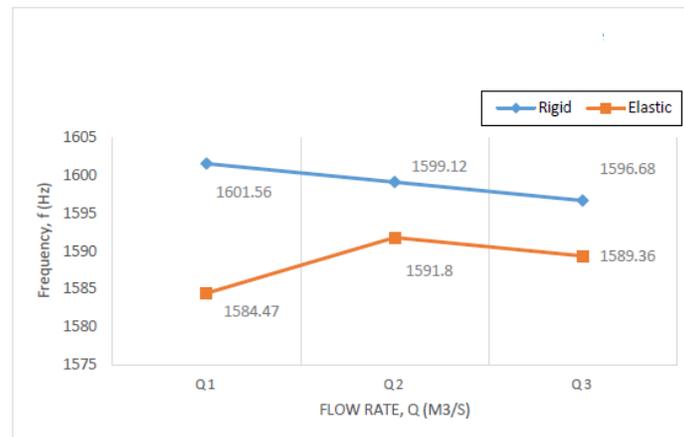

Fig. 10. Condition after Water Impact

The dominant average natural frequency for each pipe material with the increase of flow rate, the frequency of rigid pipe is higher than the elastic pipe. Therefore, for this experiment the rigid the pipe, the large the frequency occurs. According to the study by John Pickford [10] in his research found that the pipe is a rigid pipe and the valve is suddenly closed, then converted of the kinetic energy to pressure energy due to the valve closure is be absorbed by both fluids due to it compressible [10]. While non-rigid pipe which is be absorbed by the fluid due to it compressible and the elasticity of the pipe. So that for this experiment the elastic have the lower value. Therefore, it can be concluded that the elastic pipe is safer compared to the rigid pipe after impaction in pipe occurred.

4. Conclusions

The maximum average acceleration vibration in UPVC class D pipe is higher than HDPE grade PE80 pipe. Based on the tabulated data for maximum acceleration of vibration signal for time domain shows that the increase of water flow rate will increase the peak acceleration of vibration signal. This trend is same for each experiment for the type of pipe material. The acceleration vibration signal also increases with the increase the rigidity of pipe material. This is because the pressure rise in the pipe is affected by compressible of fluid and elasticity of the pipe. Therefore, it can be concluded that material of pipe will affect the acceleration vibration peak [20].

Furthermore, the second outcome of this research is the frequency of UPVC class D for rigid pipe is higher compared to HDPE grade PE80 for elastic pipe during water hammer occurred. This research is to determine the changes of frequency obtained before the condition of water hammer compare with the situation on condition after the water hammer phenomena. This water hammer phenomena occur can be analyzed by referring to the FFT frequency spectrum changing. The diagrams of FFT

frequency spectrum for water hammer phenomena start to occur. The non-rigid pipe can absorb the strain energy and reduce the speed of the pressure wave during the water hammer phenomena. Therefore, it can be concluded that more rigid the pipe wall is, and the higher the water hammer pressure will be.

The frequency and maximum average acceleration in the rigid pipe are higher than the elastic pipe. Therefore, the more effect of water hammer in pipe system is a rigid pipe which UPVC class D. In conclusion, the elastic pipe is safer compared to the rigid pipe during impaction in pipe occurred

Acknowledgement

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