Measurement of pressure wave speed in stainless-steel pipe generated by water hammer

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Abstract. This paper aims to demonstrate a measurement method of pressure wave speed in stainless-steel pipe filled with water caused by water hammer phenomenon. The pressure wave is generated using a self-developed drop impact testing equipment. An impactor is dropped to collide a buffer which then induces the water hammer phenomenon. The generated pressure and its propagation speed in the water are carefully measured here. Pressure measurement is conducted by a pressure transducer, while pressure wave speed is measured by two methods, which utilize peak time of the pressure recorded by pressure transducer and peak time of strains recorded by two strain gages positioned in a different location. These strain gages are oriented to the circumferential direction of the pipe. Measurement result shows that at 1.5 m height, impact pressure of between 0.86 to 1.16 MPa and wave velocity of 1250 m/s were obtained. From the experimental results, the characteristic of pressure wave in the water was able to be observed.

1 Introduction

The phenomenon of pressure wave propagation due to water hammer in fluid-filled pipe has been studied in both experimentally and numerically [1-3]. A comprehensive understanding on this phenomenon is very useful for designing a reliable structure in engineering applications such as durable pipe for water hammer impact application [4], crashworthiness structures [5], suspension and damping systems [6], as well as to avoid component damage due to cavitation bubble collapse occurred during operation of fluid machinery [3, 7].

The water hammer phenomenon in a piping system usually can be identified with the generation of pressure wave propagation [8]. Moreover, the mathematical models of pressure wave were developed and applied to explain the water hammer phenomenon since the mid-1800s [9, 10]. While investigating the failure behavior of the pipe body due to impact load is interesting [11, 12], characteristics of the fluid-structure interaction between the water and pipe have yet to be fully understood.

Drop impact test is one common method used to reveal the behavior of pressure wave propagation [3]. In this method, an impactor is dropped to a specimen from a specific height. The specimen is usually a pipe made of a particular material filled with compressible or incompressible fluid. When the impactor is dropped, impact energy is transferred to the fluid generating a pressure wave. Then, due to the pressure wave, the pipe experiences deformation which can be measured by a strain gage attached on the wall of pipe.

The purpose of this research is to investigate the effect of water hammer phenomenon in a stainless steel pipe filled with water by drop impact test. The generated pressure wave propagation in the water by the drop impact load is recorded by strain gages and pressure transducer, simultaneously. The speed of water pressure wave propagation in the pipe is characterized by two strain gages attached to the steel pipe with a certain distance. The time difference of peak signals recorded by two strain gages indicates the travel time of the pressure wave within the water.

2 Testing procedures and equipment

2.1 Drop impact test design

A drop impact test equipment is designed to measure the pressure and strain resulting from the shock load. Figure 1 shows the schematic diagram of measurement apparatus. Two strain gages are attached to the outer wall of pipe with a distance of 25 cm. These strain gages record the strain signal generated by the pressure wave in the water. The strain gage is mounted parallel to the circumferential direction of the pipe. Thus, the resulting strain data is a circumferential strain.

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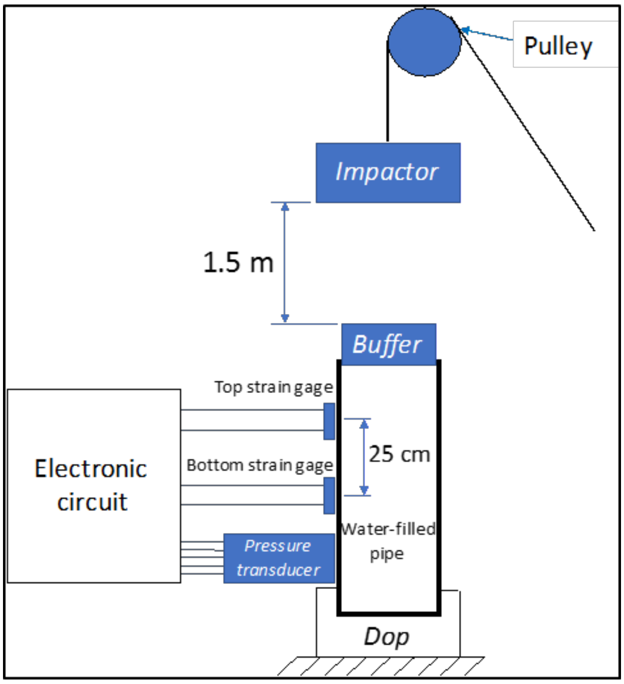

Fig. 1. Design of impact test tool front view.

The pipe surface attached by the strain gages is polished by sand paper beforehand. Then, it was swept by alcohol to remove the left dirt or grease. The strain gage is then attached by CC-33A glue and expected to dry for 24 hours at room temperature. After that, the strain gage is tested by hitting it using an eraser. If the recorded voltage is not altered, the attachment of strain gage is judged to be appropriate.

The stainless steel pipe is mounted with a pressure transducer to record the pressure wave signal. The pressure transducer is put in a G3/8x19 socket. A hole in the pipe wall is created to put the socket. The pressure transducer is then calibrated with a constant voltage excitation type of strain meter.

Prior the test, some parameters are determined as shown in Table 1. Table 2 shows the experimental scenarios for the drop impact test. These scenarios must be conducted because of limitation of strain amplifier owned in laboratory. The results of pressure wave speed and pressure value are then compared.

2.2 Measurement and signal processing

For data retrieval and processing, we develop an electronic device as shown in Figure 2. The strain gage used for strain measurement is KFG type used for general strain measurement. This strain gage has 2 legs in which each leg is associated with a Wheatstone bridge and a strain amplifier. The resulting voltage (V) signal is recorded using data acquisition and displayed in Labview Signal Express 2015 software produced by National Instrument.

Pressure transducer used in drop impact test is PW-1MPA type. It is used for pressure measurement with reference to environmental stresses around the device. This pressure transducer has an output consisting of 5 wires. Each wire is connected to a Wheatstone bridge and a strain amplifier. The resulting V signal is recorded using data acquisition and displayed in the Labview Signal Express software.

The raw data obtained from the data acquisition device is V signals versus time (t). This data includes noise from the environment which must be excluded. Using the discrete Meyer wavelet executed in Matlab®, the V signals can be filtered from the noise [13]. Further, these V signals from pressure transducer and strain gage are converted to pressure (P) versus t and strain (ε) versus t, respectively. This can be done by firstly calibrate the relationship between V signals to P and ε. The detail of the signal processing diagram is shown in Figure 3. Those data are then analysis further to obtain pressure wave speed in the water-filled pipe.

Table 1. Parameters required for initial setup of drop impact test.

Parameter	Value
Impactor Mass	12 kg
Buffer Mass	0.72 kg
Impactor initial height	1.5 m
Pipe diameter	100 mm
Pipe thickness	2 mm
Elasticity Modulus of Steel	200 GPa
Bulk Modulus of Water	2.15 GPa
Density of Water	1000 kg/m^3
Acceleration of Gravity	9.8 m/s^2

Table 2. Types of experiments of drop test impact.

Experiment	Top Strain Gage	Bottom Strain Gage	Pressure Transducer
A	yes	no	yes
B	no	yes	yes
C	yes	yes	no

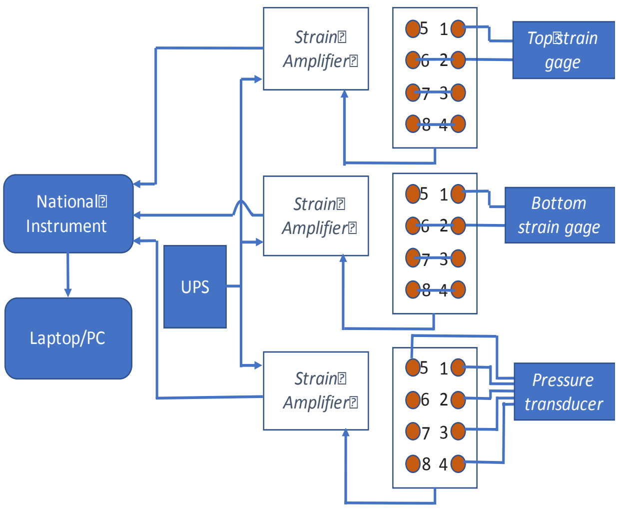

Fig. 2. The series for measurement using strain gage and pressure gage at the same time.

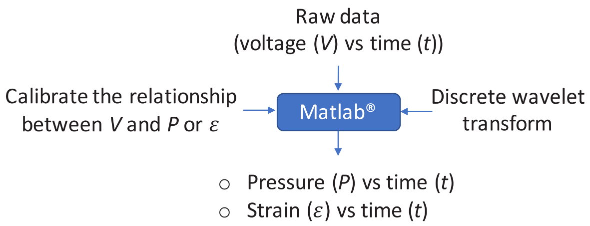

Fig. 3. Signal processing diagram.

3 Results and discussion

3.1 Peak pressure wave

For experiment A, the signals are recorded from the top gage strain and the pressure transducer. Figure 4a shows the *V* signal curve as a function of *t* from the top strain gage. The signal filtered from noise by discrete Meyer wavelet and converted to $\mu\varepsilon$ curve is shown in Figure 4b. For the pressure transducer, the *V* signal is shown in Figure 5a. It is also filtered with Meyer wavelet and converted to *P* curve as shown in Figure 5b. Similar to the experiment A, for experiment B and C, the *V* signals were also recorded. Those signals are then filtered and converted to *P* and $\mu\varepsilon$ curves. Figures 6 and 7 show results from the experiment B whereas Figures 8 and 9 show results from the experiment C.

From the results of experimental C, the *V* signals are expected to be exposed noise as shown in Figures 8a and 9a. It does not occur in the experiment A and B. Thus, the data from experiment C might not be accurate.

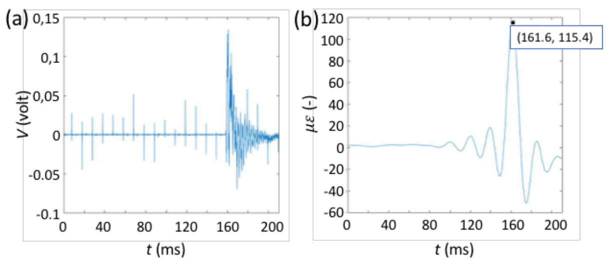

Fig. 4. Raw *V* signal (a) and $\mu\varepsilon$ signal after filtering (b) obtained from top strain gage in experiment A.

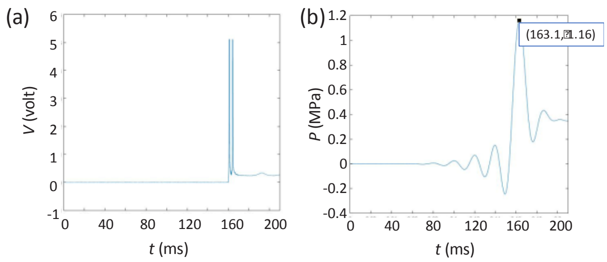

Fig. 5. Raw *V* signal (a) and pressure signal after filtering (b) obtained from pressure transducer in experiment A.

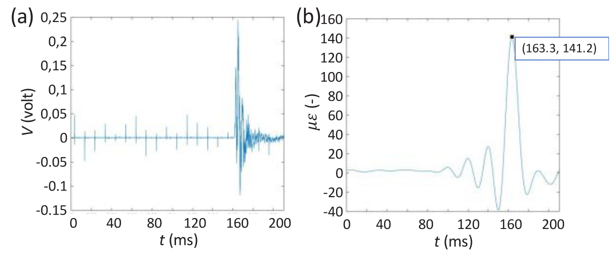

Fig. 6. Raw *V* signal (a) and $\mu\varepsilon$ signal after filtering (b) obtained from bottom strain gage in experiment B.

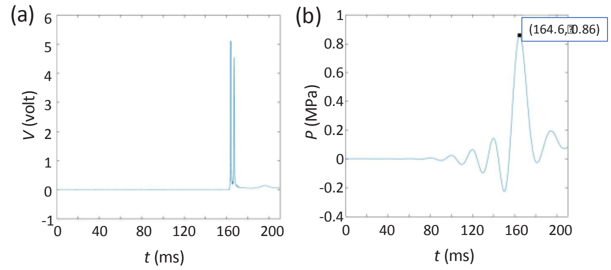

Fig. 7. Raw *V* signal (a) and pressure signal after filtering (b) obtained from pressure transducer in experiment B.

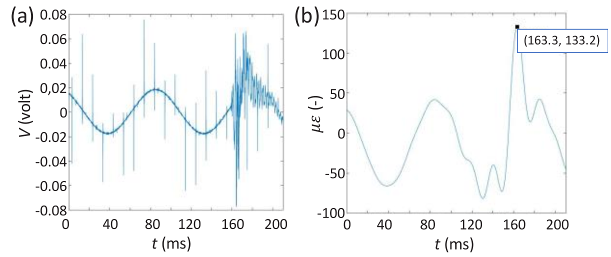

Fig. 8. Raw *V* signal (a) and $\mu\varepsilon$ signal after filtering (b) obtained from top strain gage in experiment C.

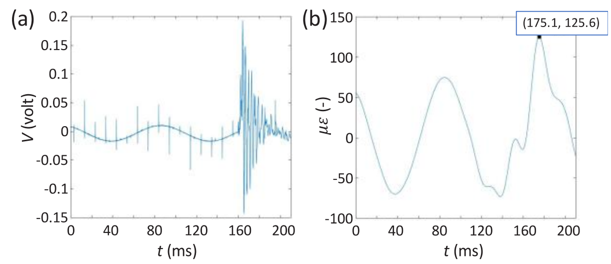

Fig. 9. Raw *V* signal (a) and $\mu\varepsilon$ signal after filtering (b) obtained from bottom strain gage in experiment C.

From Figures 4 – 9, the peak values of each graph are summarized as shown in Table 3. Based on experiments A and B, the peak pressure in water due to drop impact load is in a range between 0.86 to 1.16 MPa. Pressure that occurs in the water is known as water hammer phenomenon. The effect of this peak pressure to the pipe can be observed in the ε signals shown in Figures 4b, 6b, 8b, and 9b. It can be seen that the pipe is imposed by tensile and compressed loads for a relatively short time which causes the pipe stretched irregularly. Maximum ε

recorded in the pipe is in range between 115.4 to 141.2 $\mu\varepsilon$. In fact, the impact loads must be carefully considered in designing the fluid-filled pipe. This load with very short period can cause high strain rate which can alter the behavior of the pipe made of stainless steel from ductile to brittle.

Table 3. The results of drop impact test.

Experiment	sensor	Peak time	peak y-axis
A	Top strain gage	161.6 ms	115.4 με
	Pressure transducer	163.1 ms	1.16 MPa
B	Bottom strain gage	163.3 ms	141.2 με
	Pressure transducer	164.6 ms	0.86 MPa
C	Top strain gage	163.3 ms	133.2 με
	Bottom strain gage	175.1 ms	125.6 με

3.2 Pressure wave speed

The pressure wave speed (v_P) in water can be then calculated by using experiment A and B or experiment C only. For calculation of the v_P using experiment A and B, the pressure transducer is used as reference point. The v_P can be then calculated as follows,

$$v_P = \frac{L}{\left(t_{peak,TSG}-t_{peak,PT}\right)_A-\left(t_{peak,BSG}-t_{peak,PT}\right)_B} \quad (1)$$

Where L refers to distance between two strain gages, $t_{peak,TSG}$ refers to peak time in top strain gage, $t_{peak,BSG}$ refers to peak time in bottom strain gage, and $t_{peak,PT}$ refers to peak time in pressure transducer. By applying Eq. 1, v_P of 1250 m/s is obtained. This value is near with previous report of water hammer analysis in reference [14].

For calculation of the v_P using experiment C, the v_P can also be calculated as follows,

$$v_P = \frac{L}{\left(t_{peak,TSG}-t_{peak,BSG}\right)_C} \quad (2)$$

However, we found v_P of 21.2 m/s when using experiment C result, which is far from the result using experiment A and B. This might have occurred because the data acquisition of the strain signal was not proper. From Figures 8 and 9, noise interfering the signal is too large. Thus, the recorded V signal is floating. The noise might be generated due to not appropriate setup. The utilization of strain gages for measuring v_P directly is promising. However, the strain gage response to high strain rate must be validated further.

4 Conclusions

A drop impact test instrument for investigating the pressure wave propagation in stainless-steel pipe filled with water has been developed. This method can be used to characterize the water hammer phenomenon quickly using pressure gage and strain gage. From the experimental results, the speed of water pressure wave propagation in the test pipe is approximately around 1250 m/s. The peak pressure obtained in the experiments are in a range between 0.86 to 1.16 MPa. However, the direct measurement of pressure wave propagation in water requires further improvement due to strong noise which interfering to the measurement result. As the future work, the developed drop-impact test apparatus will be used for investigating such as the cavitation phenomenon generated by water hammer inside the pipe.

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