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Study of Acoustic Emission Response to Vortex Shedding of a Bluff Body

Fatematuz Zohora, David Holmes, Pietro Borghesani, Michael Cholette, and YuanTong Gu

Abstract
Acoustic emissions (AE) have been used to detect fluid flow disturbances such as leaks in pipes and turbulence. In such scenarios, fluid dynamics characteristics can be observed at a pipe wall using an AE sensor as a result of complex mechanical interactions. The purpose of this study is to understand the relationship between fluid dynamic force (lift force) at a circular bluff body inside a pipe, and the AE response to this force. Both experimental and numerical studies were conducted to understand this relationship. This investigation reveals that the generated lift force was weak. As a result, the pipe wall response in terms of deformation, velocity, and acceleration was small, and the AE sensor failed to detect the signals. The findings indicate that numerical study can be used as a guide to design AE condition monitoring strategies and to understand what type of disturbance profiles can and cannot be detected.

Index Terms *Acoustic Emission (AE), Numerical study, Experimental study, Bluff body, Vortex shedding*.

1 Introduction

Acoustic emission (AE) is a popular non-destructive testing technique used in condition monitoring. An AE generating event causes surface motion of a structure in the form of elastic waves. An AE sensor plays a critical role as it records this surface motion and converts it into a voltage-time waveform. Importantly, AE has been used to detect fluid flow disturbances like leaks in pipes or high turbulent flow [1]. AE technique thereby can be used for investigating the relationship between fluid dynamics, and the corresponding mechanical phenomenon at the pipe wall.

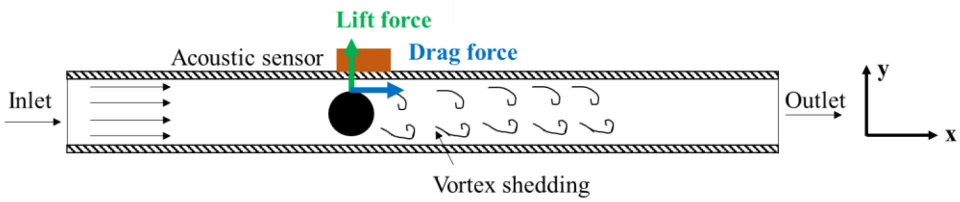

Fig. 1 Fluid dynamic forces around a bluff body

When flow passes over a body, the body creates an obstacle to the flow path and generates a wake region downstream. In this scenario, the body is known as a bluff body. Flow over a bluff is a classical problem in the fluid dynamic research area and has practical engineering applications. Flow over high-rise buildings, marine risers, bridges, cooling towers, chimneys, airfoils, tube bankers in heat exchangers, are a few of many practical engineering examples of flow over a bluff body. This type of flow often includes many complex fluid phenomena such as vortex shedding, wake flow, separation and high turbulence [2]. When the flow is obstructed by a bluff body, two types of fluid dynamic forces are generated: lift and drag force (Fig. 1). The drag force acts in the direction of the fluid flow, while the lift force is generated perpendicular to the flow direction. The fluid dynamic phenomenon changes depending on the value of these two fluid dynamic forces. The lift and drag force on a bluff body, and vortex shedding frequency are calculated from well-established equations:

$$F_D = C_D S q_{inf} \quad (1)$$

$$F_L = C_L S q_{inf} \quad (2)$$

$$q_{inf} = \frac{1}{2}\rho v^2 \quad (3)$$

$$f_s = \frac{S_t v}{d} \quad (4)$$

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where F_D and F_L are drag and lift forces on the whole cylinder in the x-direction and y-direction respectively; q_{inf} is free stream fluid dynamic pressure, f_s is the vortex shedding frequency, S_t is Strouhal number, d is dimension of the bluff body, v is fluid velocity in the pipe, S is the surface area of the bluff body.

This study aims to understand the relationship between fluid dynamic phenomenon occurring due to fluid disturbances around the bluff body– (vortex shedding in this study) and mechanical phenomenon – (responses of fluid force on the pipe wall) using AE testing technique. From Fig. 1, a circular bluff body inside a pipe generates vortices in the downstream flow. Lift and drag forces are generated at the bluff body. The force of interest in this study is lift force as it acts on the pipe wall, and vibration generates from the vortex shedding. Both events have influences on the pipe wall which can be recorded by an acoustic sensor. The extensive literature [3-5] on flow over a bluff body and the equations are helpful to estimate the lift force and vortex shedding, while the numerical and experimental study is beneficial to estimate the AE detectability.

2 Method

The method of this study (Fig. 2) involves an experimental study, and a numerical study consisting of computational fluid dynamics (CFD) & finite element analysis (FEA) simulation of flow over a cylinder. An experimental study was conducted to observe the response of the expected vortex shedding frequency in the frequency domain and then compared with the numerical study. A CFD simulation was conducted since CFD is a powerful tool that can demonstrate the fluid dynamic phenomenon occurred at the cylinder wall inside the pipe, while a FEA was performed to observe the mechanical phenomenon as a result of the fluid dynamic at the pipe wall. ANSYS Fluent and ANSYS Harmonic Response were used as CFD solver and FEA mechanical solver to investigate the fluid dynamic phenomenon and mechanical response at pipe wall respectively.

The experimental data were collected from the test-rig with an AE data acquisition system. The AE data was used for appropriate signal processing to get the response of the pipe wall in the frequency domain. The CFD study of a three-dimensional cylinder inside a pipe calculates lift force and vortex shedding on the cylinder. The lift force is then applied to the FEA model to get the response quantities (deformation, velocity and acceleration) at the pipe wall in the predetermined frequency range (around vortex shedding frequency) found from CFD simulation. The excitation frequency and magnitude of mechanical response at the pipe wall were compared from AE lab tests and FEA model.

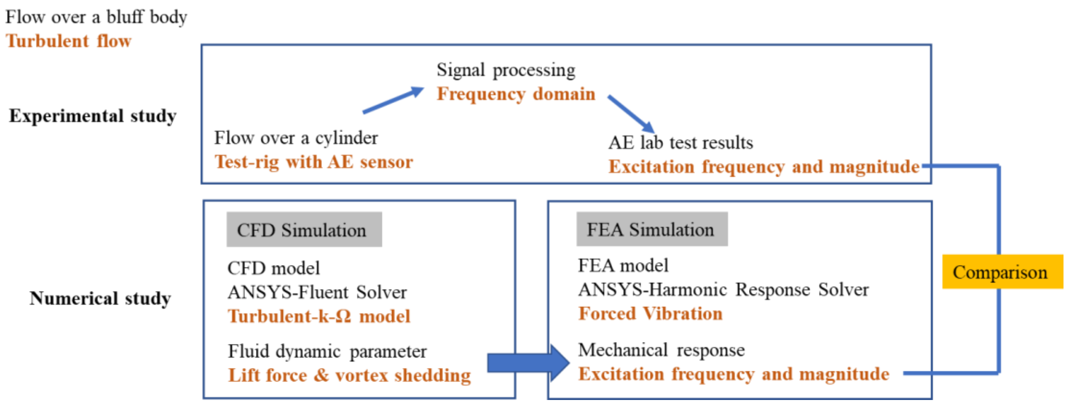

Fig. 2 Flow diagram of the method of this study

3 Numerical and Experimental test set-ups

3.1 Experimental test set-up

The experimental set-up has two parts: test-rig and AE data acquisition equipment. The pipe dimension was 1.2 m long and 125.4 mm inner diameter with 1.6 mm wall thickness and the cylinder diameter was 25mm. A flow meter and a pressure gauge were used to measure the fluid flow rate and pressure at pipe outlet respectively. A flow stabilized zone was introduced to the inlet of the pipe to make the fluid stable before it passes over the cylinder. A higher flowrate was selected to generate turbulent flow inside the pipe. Physical acoustic corporation (PAC) resonance sensor (AE R15 α) with resonance frequency 150 kHz was mounted on the surface of the pipe for capturing AE signals. The AE sensor was connected to a high-pass (100 kHz) amplifier via a pre-amplifier. The gain of the amplifier and pre-amplifier was 0dB and 60dB respectively. LabVIEW software was used for signal recording through communication with *NI 9223* module and MATLAB was used for signal post-processing. The sampling frequency for data acquisition was selected manually to 1 MHz for R15α.

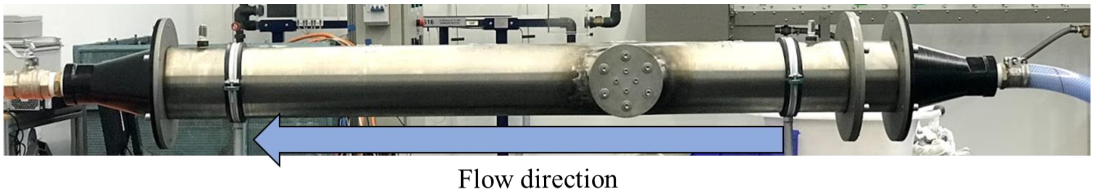

Fig. **3** Flow over a cylinder test-rig

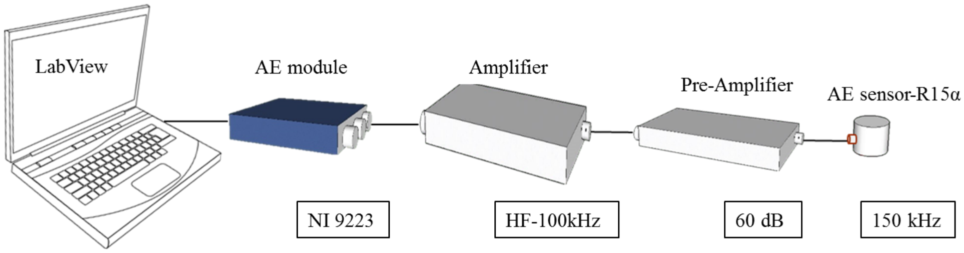

Fig. 4 AE data acquisition set-up

3.2 Numerical test set-up

A three-dimensional circular cylinder (as a bluff-body) inside a pipe was selected in this study as a vortex generator to obtain vortex shedding frequency and lift force. The geometry domains of interest for CFD and FEA study are shown in Fig. 3. The pipe and cylinder dimensions were adopted from the experimental test-rig. The material for the pipe and cylinder was Stainless steel. A high flow rate was considered for this study to ensure the flow inside the pipe is turbulent. The turbulent flow was selected because it generates higher vortex shedding frequency compared to laminar regime. A transient turbulent model (Standard k-omega) was selected for this study with velocity inlet and pressure outlet boundary condition. The Reynolds number, Re was 1.6e4 based on the mean inlet velocity inside the pipe and given dimension. The time step set to 0.001 sec for the study. Mesh and time sensitivity tests were performed to select converged mesh size and time resolution for this study.

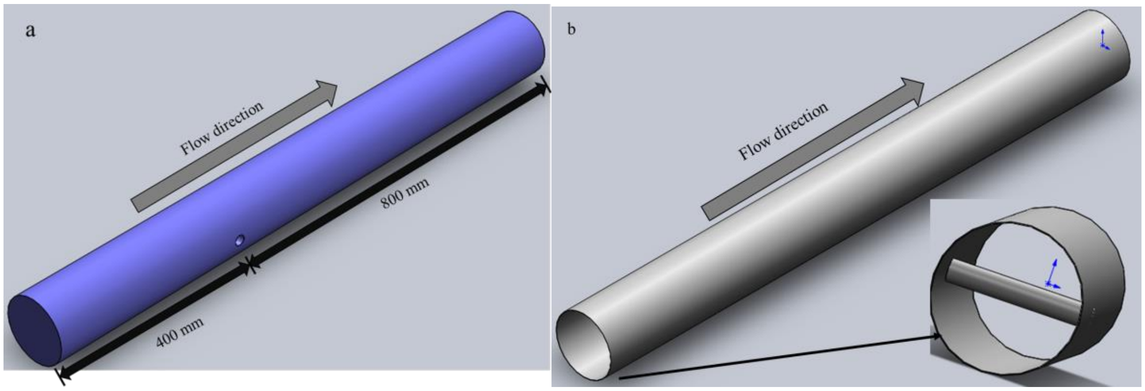

Fig. 5a CFD geometry domain, b FEA geometry domain

4 Results and Discussion

4.1 Experimental results and discussion

The experimental study was conducted to get AE voltage-time waveforms. As the area of the interest in this study is frequency, therefore, the AE response was observed in the frequency domain. The measured AE data are used to calculate fast Fourier transform (FFT) which does not show any specific frequency rather shows noise, refer to Fig. 10 Left. Vortex shedding frequency can be calculated analytically from (3) that gives 0.987 Hz. To have a closer look at the lower frequency, Fig. 10 Right plot is obtained. Yet, no specific information is extracted from the signal in the frequency domain. To get some idea of the overall frequency trend, PSD of the raw AE signal is calculated. The plot (Fig. 11) shows that the signals are amplified around 150 kHz range which is the resonance frequency range of the AE sensor used for this study. Since the analytical vortex shedding frequency is low, demodulation of the signal can help us to find the frequency. A filter-band of 125-175 kHz around the resonance frequency of the sensor is selected. The filtered signals are then used for envelope analysis using Hilbert transform.

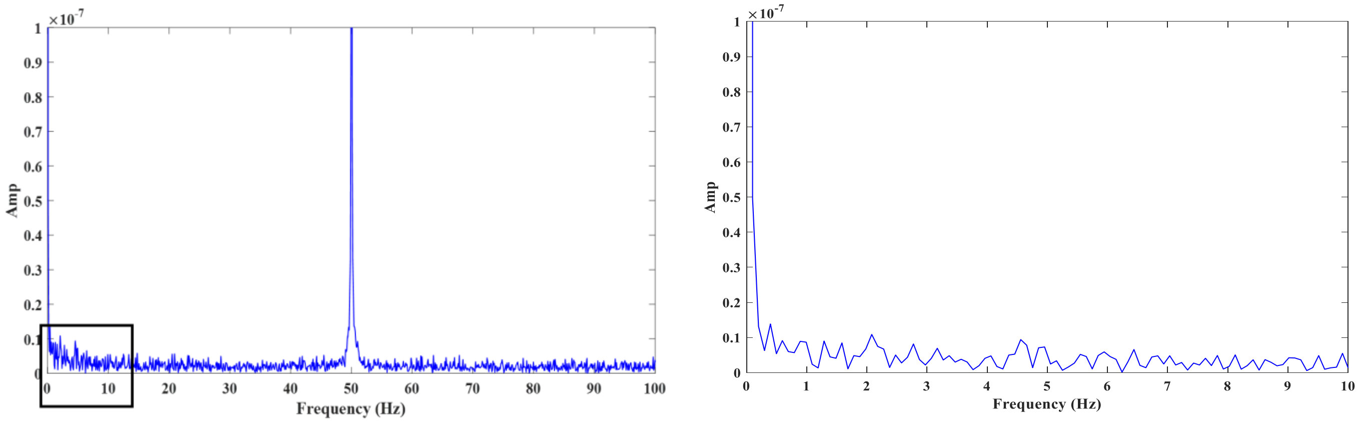

Fig. 6 Left: Frequency domain of raw AE signal, Right: Zoom around low frequency domain of raw AE signal

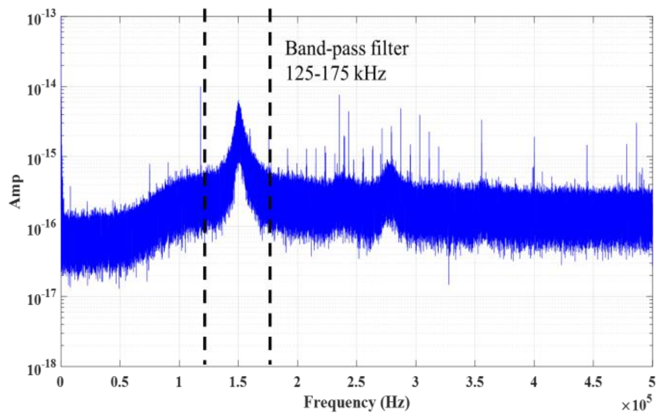

Fig. 7 PSD of raw AE signal

The demodulated signal of AE can be found in Fig. 12. The frequency range over the 100 Hz shows no specific frequency peak that can be related to the vortex shedding frequency. Hence, the results arise a few questions. Is the excitation frequency due to vortex shedding low and buried into the background noise? Is the vortex shedding generated at all in the pipe? Is the generated lift force weak that can have less impact on the pipe wall? To find the answers to these questions, a numerical study will be a helpful tool.

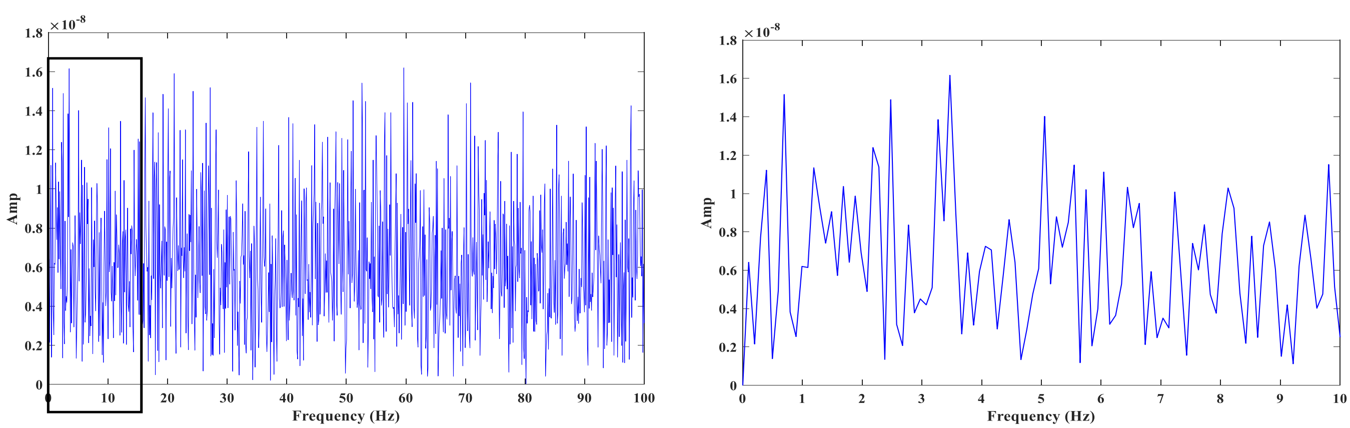

Fig. 8 Left: Frequency domain of envelope AE signal, Right: Zoom around low frequency domain of envelope AE signal

4.2 Numerical results and discussion

It was found that smooth surface circular cylinder generates stronger dynamic force and vortex shedding than rough surface circular cylinder [6]. Thus, a circular smooth surface cylinder is selected to generate a strong vortex shedding in this study. A higher Reynolds number ensures higher vortex shedding frequency refers to (3). On the other hand, it is found from (2) that lift force is function of lift coefficient in the case of the same fluid properties and geometry domain. A theoretical vortex shedding frequency value (0.9871 Hz) can be found from (3), provided that an infinite channel/pipe wall was considered. Fig. 6 demonstrates that an alternating vortex shedding is generated from the current domain. The magnitude and frequency of this alternating vortex shedding are 0.03 N and 1.249 Hz (from Fig. 7). The calculated value is accurate enough as the value is considered for a finite pipe wall (125.4 mm). The study reveals that the generated lift force was weak.

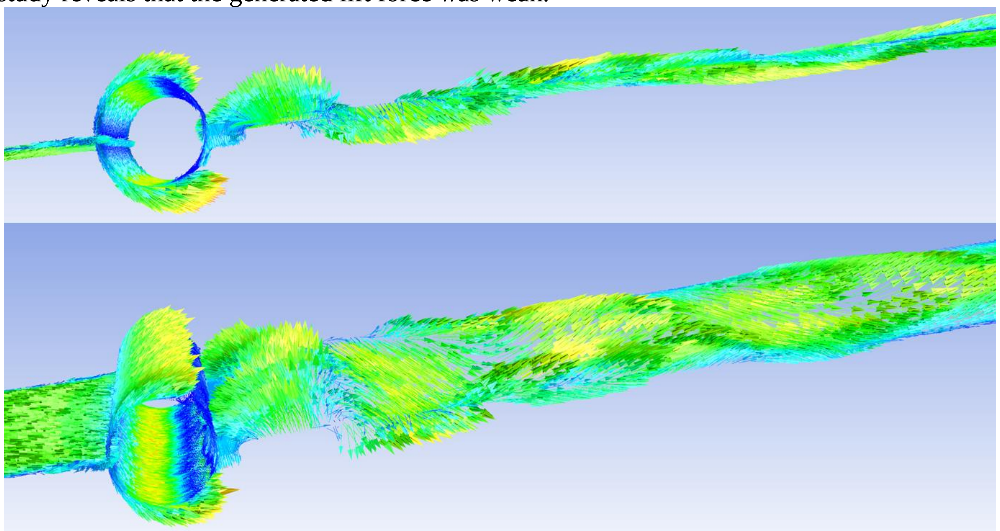

Fig. 9 Vortex shedding around a cylinder from CFD simulation

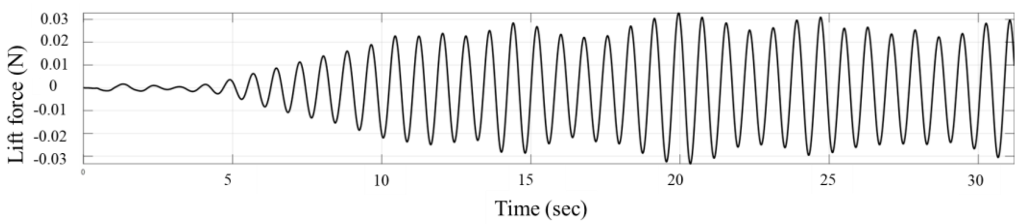

Fig. 10 Lift force generated due to vortex shedding

It is expected that this lift force and frequency of the vortex shedding have influences on the pipe wall. To obtain this influence, the lift force is applied to the pipe wall using ANSYS Harmonic Response solver. This solver solves the forced vibration equation. As per [7, 8] the input of an AE sensor is either velocity or displacement or force, while the output is voltage over time. AE wave such as lamb wave or bulk wave is complex for simulation. A simplified case considered where the mechanical response qualities deformation, velocity and acceleration are obtained as an effect of lift force on the pipe wall. So, the deformation and velocity are of great interest in this study. Before finding the forced vibration response, the natural frequency of the system is important to know. An analytical calculation shows that the weight of the test-rig is 4 kg (approx.) and the natural frequency is 579 Hz. To avoid the resonance of the system, it is essential to identify the natural frequency of the system. Through the ANSYS Modal analysis, a list of natural frequencies (Fig. 8 Left) is determined for the current system. Thereby, the natural frequency of the system can be verified. Further validation can be obtained once the system is under force vibration and shows the resonance frequency. As to determine the pipe wall response, the ANSYS Harmonic Response solver is used applying lift force to the pipe wall as can be seen from the Fig. 8 Right. The pipe responses are obtained as deformation, velocity and acceleration at the pipe wall due to the applied lift force. As expected, the responses of the weak force are insignificant. Fig. 9 left shows the deformation of the system over a range of 1-800 Hz. The resonance frequency is at 568 validate the analytical calculated natural frequency. As the frequency of the interest for this study is low (referring to previous section, vortex shedding frequency 1.249 Hz), the deformation of the pipe is observed in the range of 1-101 Hz (Fig. 9 Right). The plot shows that the magnitude of the excitation frequency is constant over the frequency range and the value is 1.15 nm. The mechanical response qualities are summarised in Table 1. The magnitude of the responses is so insignificant that the visible response on the pipe wall is not expected. The sensitivity of the resonance sensor used for this study is 75 kHz 1V/(m/s). Thereby, the velocity (from Table 1 7.25e-6 mm/s) that is generated due to the lift force cannot be recorded with sensor.

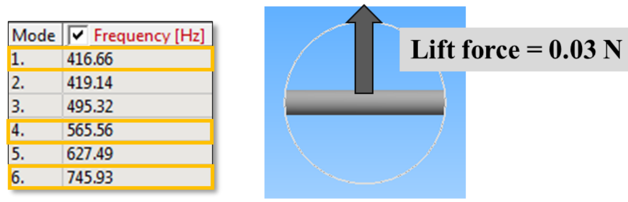

Fig. 11 Left: Natural frequencies of the system, Right: Direction of lift force acting on the cylinder

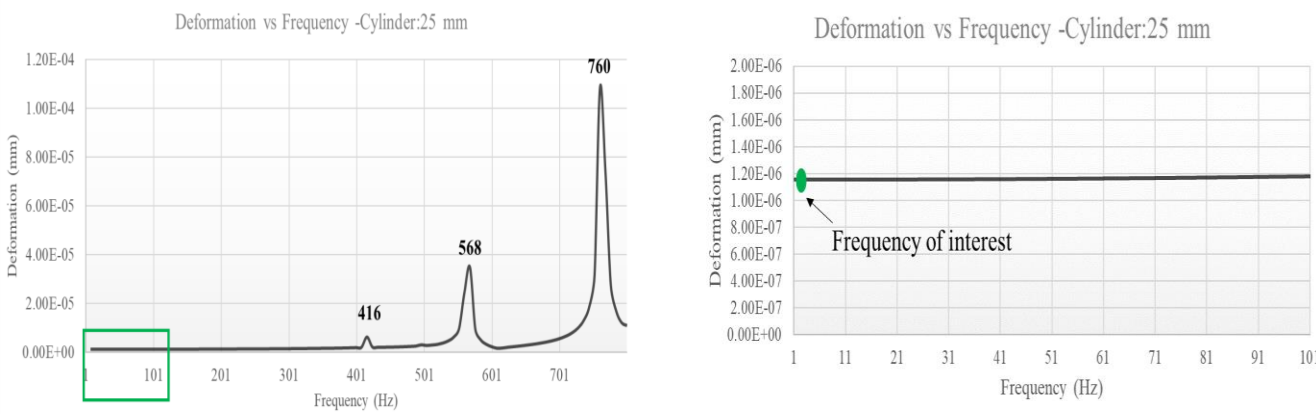

Fig. 12 Left: Deformation of pipe wall over a wide range of force vibration frequency, Right: Deformation of pipe wall over frequency of interest (1-101 Hz)

Table 1 Deformation, Velocity and Acceleration at pipe wall due to lift force

	Lift force, N	Vortex shedding frequency, Hz	Displacement, mm	Velocity, mm/s	Acceleration, mm/s^2
Cylinder:25mm	0.03	1.249	1.15e-6	**7.25e-6**	4.56e-5

Answering to the questions in section 4.1 that a vortex shedding is generated downstream of the pipe with a low frequency and a weak lift force is present. The mechanical response quantity (velocity) of this weak force on the pipe wall is insignificant to excite the AE sensor which has a sensitivity 1 V/(m/s)) for recording the signals.

5 Conclusion

The vital outcome of this study is the amount of force which is generated due to the fluid disturbance is critical to detect the AE signals in the pipe wall. The findings demonstrate that the vortex shedding induced vibration is too weak to record for a resonant AE sensor at the Reynolds number tested. The excitation frequency range was beyond capturing the AE signals. Yet, this study is valuable to understand the fluid dynamic-mechanical phenomenon relationship at the pipe from computer modelling. Understanding this relationship is of major importance in the condition monitoring fields involve fluid dynamics phenomenon, for instance, leaks in pipe, pressure tank.

Acknowledgment

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