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Flow-Induced Vibration of Cantilever Beam by One-Way Fluid Structure Interaction Approach

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Abstract: Vibration problems occur in many structural buildings and piping systems because of high flow velocities and turbulence at discontinuities in piping such as bends, tees, small bore connections and partially closed valves. This is because fluid flow is a source of energy capable of producing structural and mechanical oscillations. The most accurate description to describe the interaction between the fluid dynamic forces and structural elastic forces is flow-induced vibration. In this paper, the flow-induced vibration of simply supported cantilever beam was investigated based on one-way fluid-structure interaction (FSI). Ansys Workbench was used to simulate the dynamic behavior of the beam when subjected to air flow. There were two beam angle positions analyzed at 60° and 90° vertically, where each beam was exposed to two different fluid flow rates of 10 and 15 m/s. Fluid fluent, transient structural, modal analysis, and harmonic analysis were among the analyses used in the study. The simulation results show that the overall analysis value such as fluid pressure, velocity, total deformation, von Mises stress, and frequency response of the beam at the 90° angle are higher than the 60° beam orientation. Higher levels of vibration were also found to be affected by speed and type of fluid flow. As the beam surface area struck by the fluid flow increases, the overall values of the beam also increase. As for the conclusion, a 90° beam orientation at 15 m/s fluid flow velocity has more surface area where the fluid flow strikes than a 60° beam orientation.

Keywords: Fluid-structure interaction, flow-induced vibration, beam, vibration characteristics

1. Introduction

Flow-induced vibrations, abbreviated as FIV, are the dynamic behaviour of structures immersed in or conveying fluid flow. Fluid flow is a source of energy that can cause structural and mechanical oscillations [1,2]. Flow-induced vibrations are the most accurate depiction of the interaction of a fluid's dynamic forces with a structure's inertial, damping, and elastic forces. It can happen in a structural building or in high-speed turbulent fluid pipe configurations. Generally, FIV can affects a wide range of engineering applications, including bridge decks and skyscrapers. Due to the speed of fluid passing over structure, it vibrates and eventually fails catastrophically if not properly controlled [3,4]. On the other hand, fluid-structure interaction or well-known as FSI is the interaction of some movable or deformable structure with an internal or surrounding fluid flow [5]. FSI is used in many industries such as civil engineering, aviation, shipping, marine and earthquake geology.

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FSI involved fluid mechanics, solid mechanics, dynamics, computational mechanics, and other disciplines, in which its purpose is to investigate the mechanical action of all kinds of behaviour under flow field, and the flow field effect under the structural deformation or movement [6,7]. A cantilever beam is a rigid structural element that is supported at one end and has free ends. The cantilever beam can be made of either concrete or steel, with one end attached to a vertical support. A variety of engineering applications use this basic mechanical structure [8]. Since it is supported from just one end, cantilever beam deflects more than most other types of beams. There are several different styles of cantilever beams and trusses used in real-world constructions such as building and bridge construction.

The objective of this study is to evaluate the performance of one-way FSI modelling technique on a simply supported cantilever beam by varying fluid flow velocities and angle positioning of the beam. The interaction of the cantilever beam with the fluid flows provides insight into transient flow fields, dynamic meshing, and the reciprocal interaction of the solid structure and the fluid flow. The simulation was performed using Ansys Workbench which is a commercial tool that is often used in industry practice to determine the cantilever beam's natural frequency, mode shape, and frequency response.

1.1 One-Way Coupling FSI

At the boundary between fluid and solid – the fluid-structure interface, information for the solution is shared between the fluid solver and the structure solver. The information exchanged is dependent on the coupling method [9]. For one-way coupling, the deformation of the structure is affected by the motion of the fluid flow and vice versa. An example of this type is a ship's propeller. Figure 1 shows the solution procedure for the one-way coupling method. In this method, the fluid field is first resolved until the desired convergence. After that, the calculated pressures at the interface are transferred to the structural model. Then, the structural model is repeated until the convergence criterion is reached.

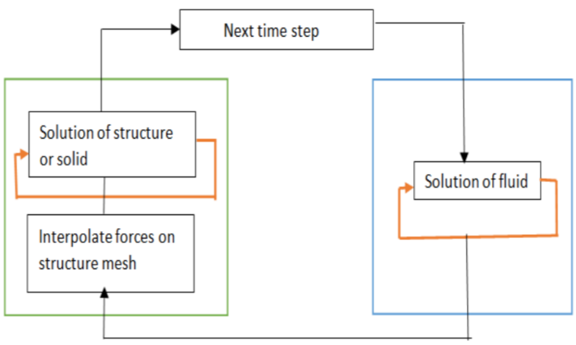


Fig. 1 – One-way coupling method [10]

2. Methodology

The beam is modelled using Ansys Design Modeler and Space claim, both of which are included in the Ansys Workbench 2020 R2. Aluminium alloy and air are used as the default material properties for the beam and fluid domains in Ansys. The materials' specifications and properties are depicted in the Table 1.

Table 1 – Material properties of aluminum alloy

Specification	SI/Metric Unit
Density	2770 kg/m^3
Young's Modulus	7.1×10^7 Pa
Poisson ratio	0.33
Shear Modulus	2.6692×10^{10} Pa

2.1 Models Preparation

The simulations are carried out at two different beam angle placements of 60° and 90°, and at two different flow speeds of 10 m/s and 15 m/s. Both beam configurations are contained within a rectangular enclosure. Figure 2 shows an example of configuration for 90° beam configuration, while Figure 3 shows the beam dimension used in the study.

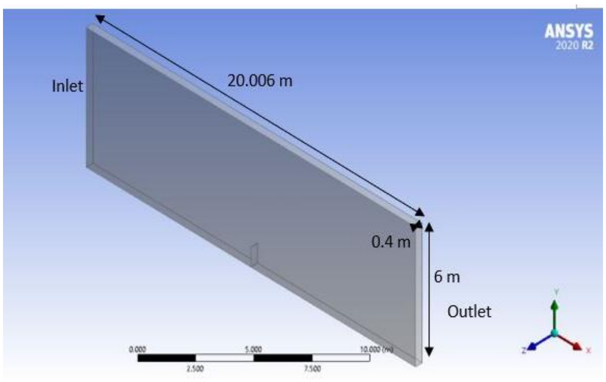


Fig. 2 – Configuration for 90° beam orientation

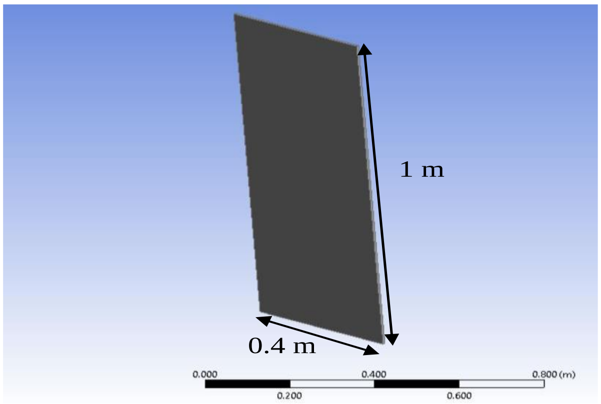


Fig. 3 – Geometry of beam

2.2 Ansys Simulation

Figure 4 depicts four measurement tools used to achieve results of the study. These four tools were Fluent, Transient Structural, Modal, and Harmonic Response. The air pressure exerted on the beam was calculated using fluid flow (fluent). The natural frequencies and mode shape of the beam were determined using modal analysis, while the frequency response was using the harmonic response. Additionally, it was used to analyze the amplitude response to specific frequency excitations.

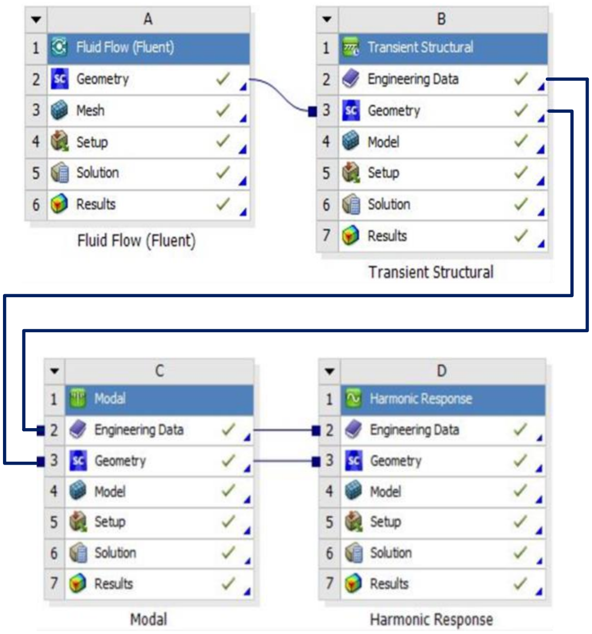


Fig. 4 – Analysis system used in Ansys Workbench

3. Results and Discussion

3.1 Pressure Distribution in Fluid Domain

When the flow around the beam is studied, a large pressure is exerted on the beam's front surface. Figures 5 and 6 illustrates a side view of a fluid pressure contour beam with a 90° and 60° orientation, respectively at a 15 m/s air flow speed, and Table 2 summarises the fluid pressure comparisons for the fluid domain.

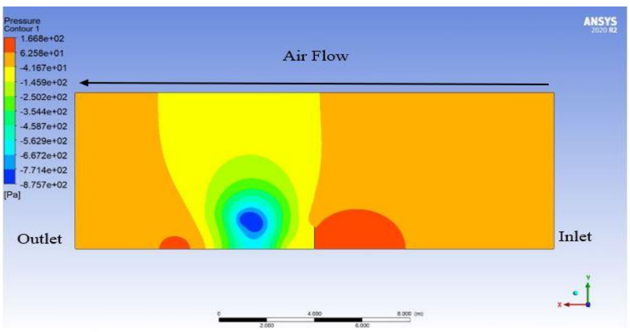


Fig. 5 – Pressure contour of 90° beam orientation

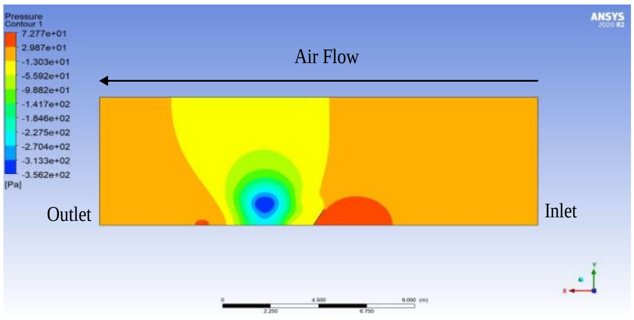


Fig. 6 – Pressure contour of 60° beam orientation

The significant observation is the pressure difference between the front and back surfaces of the beam. At 15 m/s air flow speed, the overall pressure distribution under 90° beam orientation is greater than under 60° beam orientation at both speeds as can been seen from Table 2.

Table 2 – Fluid pressure comparison for both beam orientation and speed

Beam Orientation	Max Pressure (Pa)	
	10 m/s	15 m/s
90°	7.409e+01	1.668e+02
60°	7.277e+01	1.607e+02

3.2 Equivalent Von-Mises Stress in Structural Domain

The flexible cantilever beam is chosen to be discussed for the von-Mises stress result analysis because it is the structural region affected by the fluid flow. The deformed beam behaves similarly under two different beam orientations and air flow speeds, with larger deformation at the lower part of the beam and smaller deformation at the upper part of the beam. The main distinction between them is the magnitude of the stress distribution [11]. As shown in Table 3, the 90° beam orientation has the highest value in Von-mises at 15 m/s speed air flow.

Table 3 – Von-Mises comparison for both beam orientation and speed

Beam Orientation	Max Stress (Pa)	
	10 m/s	15 m/s
90°	6.2858	14.165
60°	6.1582	13.612

3.3 Total Deformation in Structural Domain

The investigation is furthered with Transient Structural analysis, which looked at the total deformation of the cantilever beam in two different beam orientations at two different air flow speeds. Figure 7 depicts the total deformation of a fixed-free end beam with a 90° beam orientation and a speed of 15 m/s. For both conditions of beam orientation, the maximum total deformation occurs at the beam's farthest end, where the fluid flow strikes the beam. This occurs because of the beam's bottom support, thus deformation on the bottom beam is minimal [12].

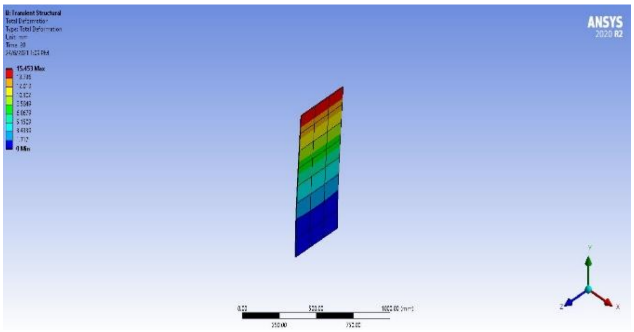


Fig. 7 – Total deformation of 90° beam orientation

Table 4 compares the total deformation of a cantilever beam with different beam orientations and fluid flow speeds. It is discovered that the greatest deformation occurs at a beam orientation of 90° at a flow speed of 15 m/s, while the smallest deformation occurs at a beam orientation of 60° at a flow speed of 10 m/s.

Table 4– Total deformation comparison for both beam orientation and speed

Beam Orientation	Max Deformation (m)	
	10 m/s	15 m/s
90°	6.8674	15.451
60°	6.7449	14.888

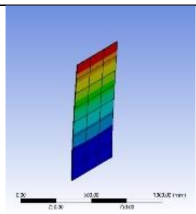
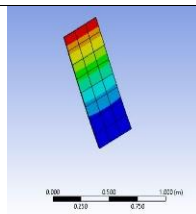
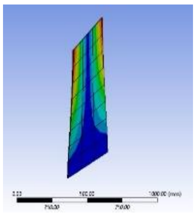
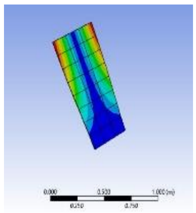
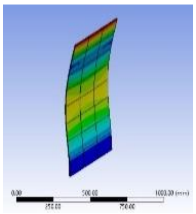
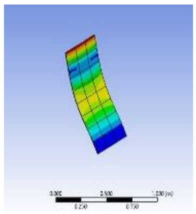
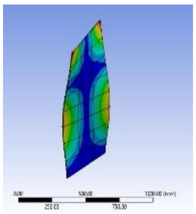
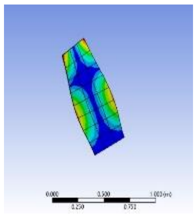
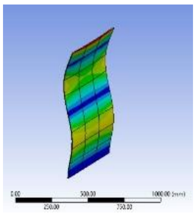
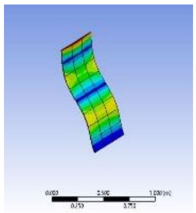
3.4 Modal Analysis of Cantilever Beam

Five natural frequencies are used to determine the orientation of a cantilever beam. The natural frequencies remain constant regardless of flow rate. The comparison of both beam orientations of natural frequencies is shown in Table 5. Since both orientation shares similar material properties and beam dimensions, both orientation shares same value for mode shape and natural frequencies, as shown in Table 6.

Table 5 – Natural frequencies for both beam orientation

Mode (n^{th})	Natural Frequency (Hz)	
	90°	60°
1	5.1355	5.1355
2	26.265	26.265
3	32.017	32.017
4	83.966	83.966
5	90.222	90.222

Table 6 – Mode shapes for both beam orientation

Mode (n^{th})	Mode Shape	
	90°	60°
1		
2		
3		
4		
5		

3.5 Harmonic Response Analysis of Cantilever Beam

Harmonic Response Analysis is used to investigate a system's response to excitation over a specified frequency range. The beam's first natural frequency has been chosen to be 5.1355 Hz. Harmonic frequency analysis is performed on all fluid flow speeds and beam orientations between 0 and 40 Hz. Figure 8 and 9 illustrates the harmonic response for both beam orientations at both speeds.

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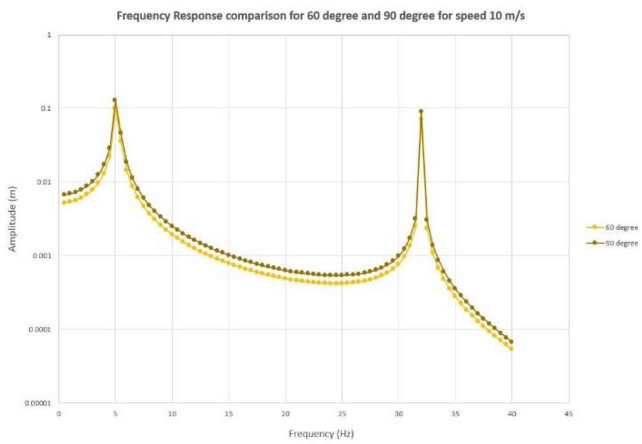

Fig. 8 – Frequency response comparison for 90° and 60° beam orientation at 10 m/s

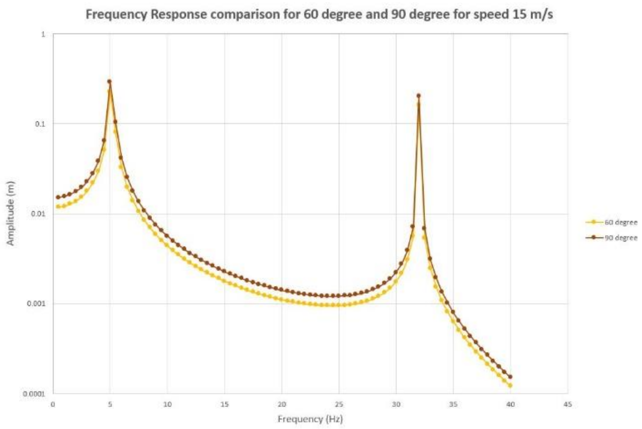

Fig. 9 – Frequency response comparison for 90° and 60° beam orientation at 15 m/s

As can be seen, there is a single peak on the curves whose frequency is identical to 5.1355 Hz. As can be seen, there is a single peak on the curves whose frequency is identical to 5.1355 Hz. There is a maximum amplitude, and the amplitude in a 90° beam orientation at a speed of 15 m/s is significantly greater than in a 60° beam orientation. There is a maximum amplitude, and the amplitude in a 90° beam orientation at a speed of 15 m/s is significantly greater than in a 60° beam orientation.

4. Conclusion

In this present study, we have demonstrated that the 90° beam orientation has a higher rate of pressure dispersion than the 60° beam orientation. Furthermore, the total deformation under 90° beam orientation is greater than under 60° beam orientation due to orientation differences. Similarly, it can be seen in the frequency and vibration level. Higher vibration level is also affected by the speed and type of fluid flow. In a nutshell, these studies show that the fluid structure interaction of the beam is affected by its 90° and 60° orientations, since the 90° beam orientation has more surface area where the fluid flow strikes than the 60° beam orientation, therefore resulting in a higher overall value.

Acknowledgement

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