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Numerical Simulation of Fixed-Free End Beam's Modal Behaviour using Two-Way Coupled Fluid-Structure Interaction Approach

Mathan Sambu[1], Izzuddin Zaman[2,*], Bukhari Manshoor[2], Amir Khalid[2], Shiau Wei Chan[3], Ahmed A. Abuhatira[4], Hwa Li Tey[5]

[1] Faculty of Engineering, Built Environment & Information Technology, SEGi University, 47810 Petaling Jaya, Malaysia
[2] Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Malaysia
[3] Faculty of Technology Management and Business, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Malaysia
[4] Nuclear, HE Engineering and Science, Lakes College West Cumbria, Workington, United Kingdom
[5] Reda Production Systems, 7 Benoi Cres, 629971, Singapore

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ABSTRACT

The fluid flow velocity stands as a pivotal parameter with a great influence on the mutual interaction between the fluid domain and structure. This paper focuses on structural deformation, structural velocity, von-Mises stress and frequency response of a fixed-free end beam using two-way coupled fluid-structure interaction within ANSYS Workbench. The parameters such as deformed fluid pressure and velocity were analysed across three diverse flow regimes: laminar, transitional and turbulent – each aligned with distinct fluid velocities. The outcomes show that the total deformation, velocity and von-Mises stress distribution of the fixed-free end beam increase as the inlet fluid velocity increases. As a result, the pressure and velocity distribution in the fluid flow which receiving the resultant or leftover structure deflection also increases as the incoming fluid velocity increases. Furthermore, the analysis probes the frequency response in turbulent flow conditions reveals higher values compared to laminar and transitional flows, albeit within the same natural frequency domain. This observation marks significant vibrational characteristics found in the presence of turbulent flow dynamics.

1. Introduction

Making alterations becomes a formidable challenge in the realm of construction and mechanical engineering once a structured building or functional mechanical equipment undergoes the manufacturing process. To enhance mechanical properties and optimize features during the early stages of development, current engineering practices heavily rely on computational-based numerical analysis methods. These methods utilize sophisticated software to model and predict real-time situations, enabling recommended modifications that align with desired outcomes [1,2]. Such

* *Corresponding author.*
E-mail address: izzuddin@uthm.edu.my

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engineering endeavors frequently entail the interaction between fluids and structures, a commonplace occurrence with far-reaching implications.

In essence, the fluid-structure interaction (FSI) paradigm encapsulates the intricate interplay between structures and the fluid environments that envelop them. Viscous effects within a three-dimensional framework and unsteady aerodynamic effects are adeptly captured through Computational Fluid Dynamics (CFD), which draws on fundamental data sourced from both fluid dynamics and structural mechanics [3]. For instance, in the context of offshore platform assemblies, hanging bridges, and high-rise buildings, the structural integrity is profoundly influenced by forces exerted by turbulent wind, and other fluid interactions [4].

Fluid-structure interaction, at its core, involves a reciprocal relationship wherein the motion of a structure interacts with the flow of the surrounding fluid. This dynamic coupling predominantly manifests when the structure interacts with either internal or external fluid flows. Notably, advancements in this field, as pioneered by Felippa *et al.,* [5] and extended by researcher Wang *et al.,* [6], have led to embedded computational frameworks that resolve equations within a single-phase domain encompassing both fluid and structure. This framework has paved the way for addressing multiphase complexities, failures, and fatigue pathways.

Recent years have witnessed a burgeoning body of literature delving into fluid-structure interaction, primarily through simulation studies as illustrated in Figure 1. Noteworthy applications encompass aircraft wings, wind turbine blades, aerospace components, and even vehicular systems. In the realm of wind turbine research, López *et al.,* [7] explored the advantages of employing an elastic-flexible membrane blade concept that adapts its geometry to inflow, altering its aerodynamic properties. Similarly, Rüberg and Cirak [8] embarked on an ambitious exploration involving two-material interactions, resulting in insights that guide future material modeling.

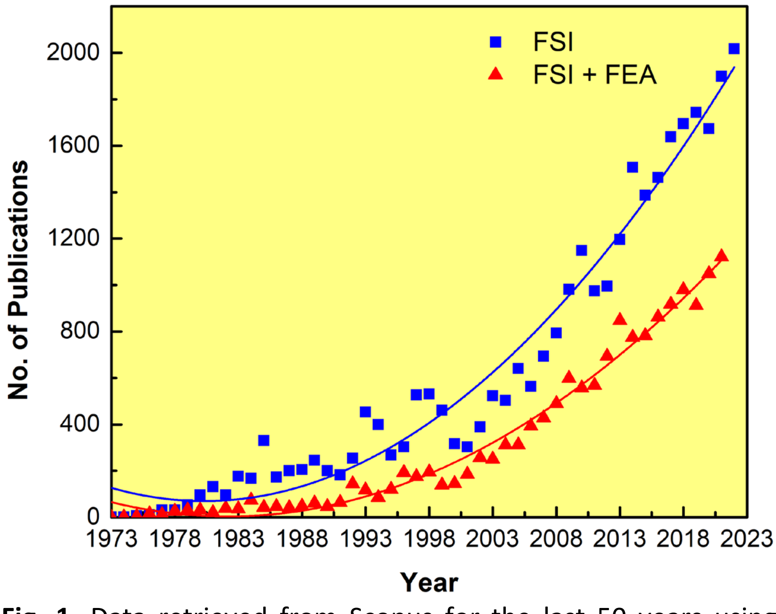

Fig. 1. Data retrieved from Scopus for the last 50 years using keywords “fluid-structure interaction” and combination ““fluid-structure interaction and finite element analysis”

Wind turbines, integral to renewable energy generation, have been subject to intensive study. Heinz *et al.,* [9] illuminated the potential of FSI in unveiling vortex-induced vibrations within wind turbine designs. The study concluded that FSI-based predictions of dynamic responses, such as vibration, trumped traditional methodologies like the boundary element method. Beyond wind turbines, diverse industries harness FSI principles to optimize performance [10,11]. The automobile sector employs FSI strategies to enhance lean combustion efficiency, addressing the acoustic pressure oscillations engendered by turbulent flames [12,13]. Additionally, in marine engineering, FSI concepts grapple with the complexities posed by variable oceanic conditions [14,15]. Notably, Ma *et al.,* [16] underscored the significance of ocean waves and their interplay with structures, shedding light on the unique challenges faced in marine FSI scenarios.

However, despite the advancements in computational tools and the extensive investigation of fluid-structure interactions (FSI), a specific research gap has persisted, particularly in the realm of structural beams. In the application of structural beams in real life, there are various types of fixed-free end beams and trusses in civil works such as building and bridge constructions. While considerable research has been conducted on fluid-structure interactions, most of these studies have predominantly focused on one-way fluid-structure coupling, leaving a notable gap in our understanding regarding the influence of fluid velocities on mechanical properties, especially stress, in the context of specific beam configurations. Notably, common fixed-free end beams, supported only from one end, exhibit distinct deflection characteristics, which can be significantly impacted by fluid-induced forces [17,18].

The present study builds upon this rich landscape by investigating the impact of fluid flow velocities on the dynamic behaviour and response of fixed-free end beams. Utilizing the ANSYS Workbench software, we embark on a comprehensive exploration of the two-way fluid-structure interaction phenomenon. Through transient analysis, this investigation aims to unravel the intricate relationship between fluid flow velocities and structural dynamics.

2. Two-Way Coupling Fluid Structure

The FSI coupling method is instrumental in managing the interaction between blocks within a nonlinear equation system. It is critical to have a reliable coupling method, especially for the underweight structure that are susceptible to changes in fluid mechanics forces [19]. This methodology necessitates solving two domains within a coupling scheme: the fluid field dynamics and the structural dynamics. The exchange of response or impact at the fluid-structure interface is a shared responsibility, spanning both fluid and structure domains.

Two-way coupling refers to a fluid-structure interaction approach where the feedback from the structural deformation influences the fluid flow, creating a bidirectional interaction [20]. This means that the structural deformation or boundary displacement must also be incorporated and communicated back to the fluid solver in real-time. One-way coupling, on the other hand, involves the influence of the fluid flow on the structure without considering the feedback from the structural response on the fluid dynamics. The stability of a coupling scheme, which is a measure of the system's ability to avoid spurious accumulation of energy due to numerical inconsistencies, is influenced more by whether the coupling is realized in an explicit or implicit manner rather than whether the coupling is unidirectional or bi-directional. In this study, an implicit coupling approach is adopted, which typically provides greater stability, especially in regimes with significant density ratios between the fluid and the structure [21].

Two-way coupling typically offers heightened stability for analyzing fluid-structure interactions involving substantial deformations, particularly when the structural behavior significantly affects the fluid domain [22]. Figure 2 displays an overview of the solution algorithm employed in two-way coupling for fluid-structure interaction. Prior studies have revealed that, in comparison to one-way coupling, two-way coupling demonstrates superior energy conservation at the interface [23].

Noteworthy investigations have convincingly highlighted that under the one-way coupling method, there's a higher likelihood of data loss between field modeling and simulation data transfer [24].

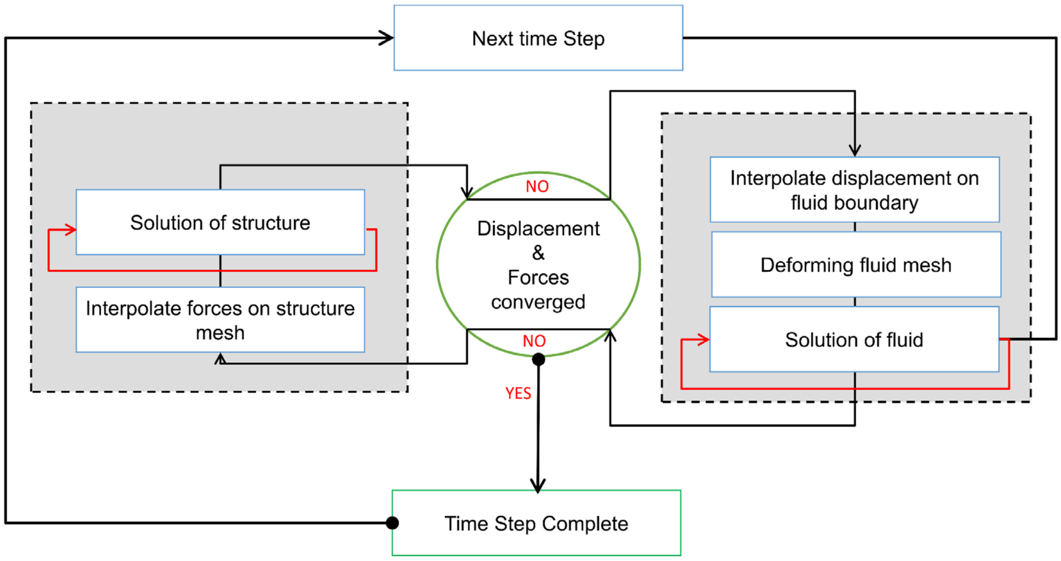

Fig. 2. Solution algorithm for two-way coupling

Consequently, the choice between one-way and two-way FSI techniques is often dependent on the specific case model and domain requirements. In cases where complexity necessitates heightened predictive capabilities, the two-way model becomes the more suitable option. Adopting the principles of the FSI solver method, La Spina *et al.,* [25] concluded that under certain conditions where compressibility is introduced in the fluid, the two-way coupling method becomes advantageous in most FSI scenarios. Furthermore, it has been established that at higher flow velocities, two-way FSI yields distinct advantages over one-way FSI, displaying enhanced realism in practical applications [26,27]. This dichotomy in FSI characteristics becomes pronounced when velocities are elevated.

3. Design and Modelling

In this comprehensive modeling and simulation process, the ANSYS Workbench 2020 R2 environment acts as a cohesive platform, allowing for the accurate exploration of fluid-structure interaction dynamics in fixed-free end beams. The process is depicted in Figure 3, illustrating the simulation flow chart within ANSYS Workbench.

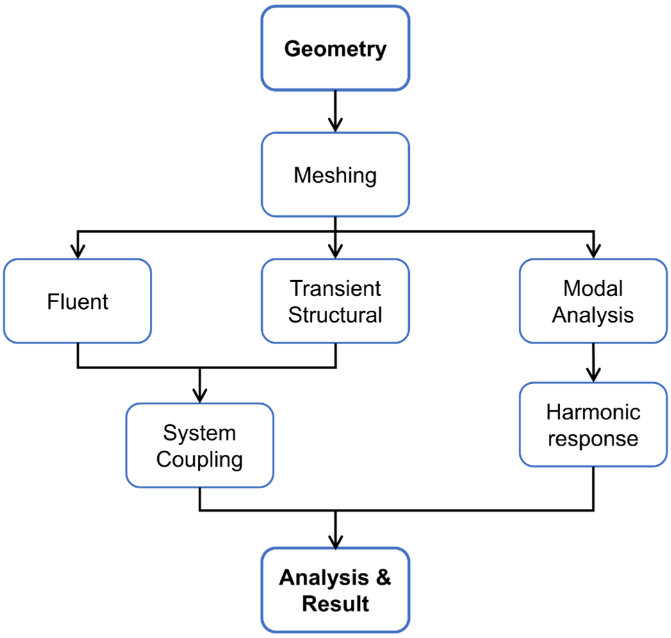

Fig. 3. Simulation flow chart in ANSYS Workbench

3.1 Fluid-Structure Interaction Model

The modeling of the fluid domain and fixed-free end beam is accomplished using Design Modeler, an integral component of ANSYS Workbench 2020 R2. Details dimension can be seen in Figure 4. Aluminum alloy was selected for the beam due to its flexibility, thus suitable for studying deformation effects caused by fluid flow. The properties of both the beam and fluid are shown in Table 1. The mesh details, including nodes and elements, are provided in Table 2. The number of elements and nodes defined for both solid and fluid domains are sufficient to obtain mesh independence, ensuring that further refinement does not significantly change the results.

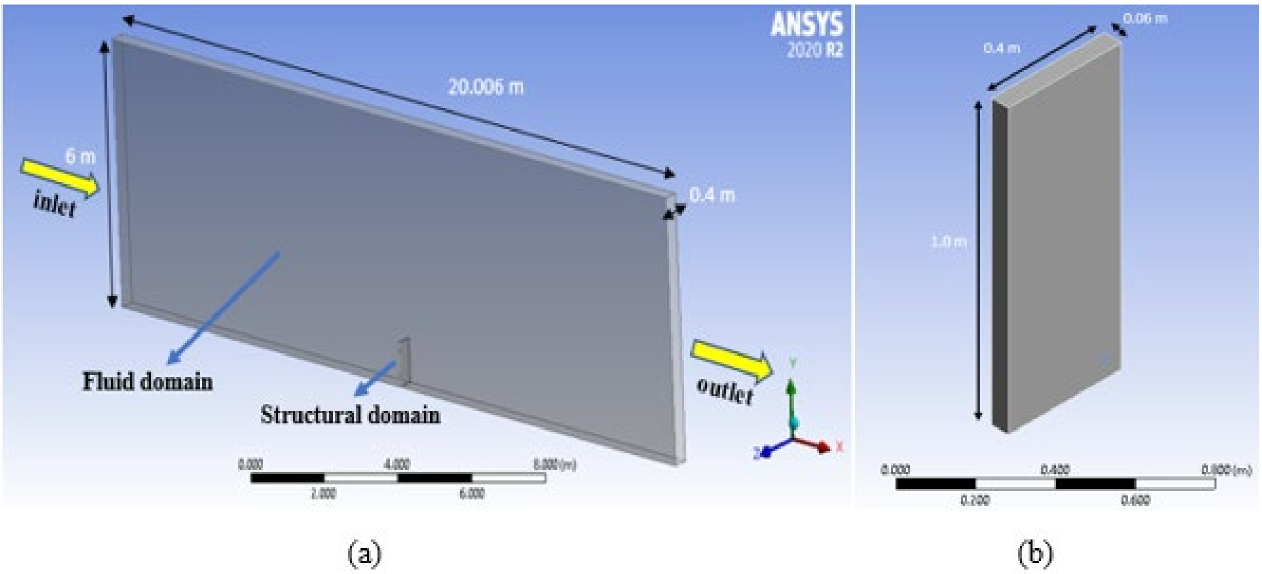

Fig. 4. (a) The overall computational geometry of 3D modelling (fixed-free end beam and water domain) (b) The dimensions of fixed-free end beam model

Table 1
Properties of materials

Specification	Aluminum Alloy	Water
Density	2770 kg/m^3	998.2 kg/m^3
Young's Modulus	71 MPa	N/A
Poisson's Ratio	0.33	N/A
Viscosity	N/A	0.001003 kg/ms

Table 2
Mesh statistics for structure and fluid

Mesh	Fixed-Free End Beam	Water Domain
Nodes	353	61610
Elements	40	48200

3.2 Fluid Velocity and Reynolds Number

Three different fluid velocities were chosen to simulate laminar, transitional, and turbulent flow conditions. The Reynolds number, a dimensionless quantity that helps predict flow patterns, was calculated for each case, as summarized in Table 3, which also includes the models adopted for each type of fluid flow during the Fluent Models setting.

Table 3
Summary of the fluid flow parameters and models

Fluid flow	Velocity, V (m/s)	Hydraulic diameter, D_H (m)	$Re = \frac{\rho \times V \times D_H}{\mu}$	Models
Laminar	0.0003	0.75	223.92 ($Re < 2300$)	Laminar
Transition	0.0040	0.75	2,985.64 ($2300 < Re < 4000$)	Transition k-kl-omega
Turbulent	30.0000	0.75	22392323.03 ($Re > 4000$)	k-epsilon

3.3 Simulation Method

The FSI analysis was performed using a two-way coupling simulation method, integrating multiple analysis systems in ANSYS Workbench. Initially, the Transient Structural and Fluid Flow (Fluent) analysis systems were set up, followed by the incorporation of a System Coupling system to connect both structural and fluid systems. The shared geometry between the structural and fluid systems enabled two-way FSI analysis. Meshing was generated for the solid part with fixed support applied at the bottom of the beam, and boundary conditions, including inlet fluid velocities, were specified for different flow cases.

The fluid model chosen in Fluent was incompressible and transient (unsteady state), ensuring the accurate simulation of fluid dynamics over time. The System Coupling setup managed data transfer between the fluid and structural systems, with specific time advancements and convergence criteria to ensure accurate simulation results. Modal analysis was performed to determine the natural frequencies and mode shapes of the beam, and harmonic response analysis evaluated the beam's response under harmonic loading, considering different fluid velocities.

Figure 5 depicts these five main components performed within the Project Schematic. Furthermore, to validate the natural frequencies and mode shapes of the beam, the results obtained from SolidWorks simulation were compared with those obtained from the present analysis. While the SolidWorks simulations provide a useful benchmark, it is important to note that differences in numerical setups and meshing strategies can influence the results. Therefore, the comparison serves as a validation of trends rather than an absolute verification of accuracy.

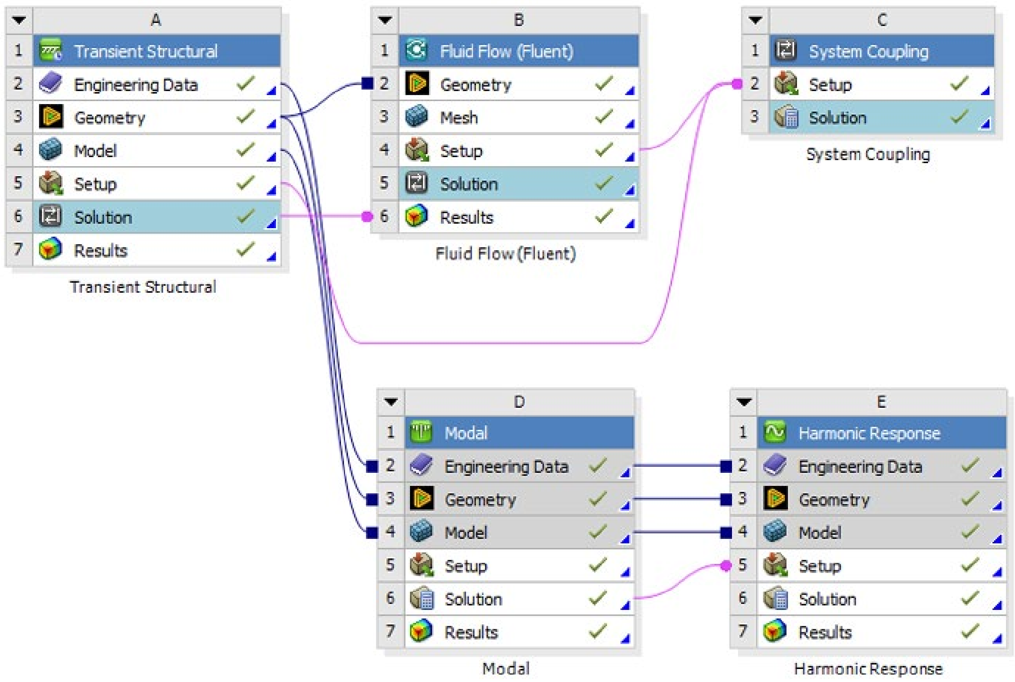

Fig. 5. The overall diagram system in ANSYS Workbench

3.4 Boundary Conditions and Initial Conditions

Boundary conditions were applied to ensure realistic simulation scenarios. For the fluid domain, velocity inlet conditions were specified, and the outlet was set to a pressure-outlet condition. The structural domain had fixed support at the base of the beam, with fluid-structure interfaces defined for interaction.

3.5 Numerical Methods

The numerical methods employed include the finite element method (FEM) for the structural analysis and the finite volume method (FVM) for the fluid analysis. These methods were selected for their robustness in handling complex fluid-structure interactions.

4. Results and Discussion

4.1 Fluid Field Analysis/ CFD Domains Results

Figure 6 illustrates the contour plot capturing the qualitative analysis of pressure distribution and velocity fields within the fluid domain surrounding the fixed-free end beam across laminar, transition, and turbulent conditions. The snapshots were taken at the end of 20 seconds of simulation. The simulation data reveals that the frontal surface of the free-end beam experiences elevated pressure, while a region of lowered pressure is observed at the beam's free edge, as showcased in Figure 6. It becomes evident that the pressure discrepancy increases notably with the incremental inlet fluid velocity, aligning with the findings of Malazi *et al.,* [28]. Notably, the overall pressure distribution is higher under turbulent flow in comparison to laminar and transitional flows. It is expected that as the fluid inlet velocity increases, the residual stress from the deformation of the flexible fixed free-end beam will be applied to the fluid domain with a proportionally greater force. Table 4 tabulates a comprehensive comparison of maximum pressure and velocity values under laminar, transition, and turbulent flows.

Table 4
Summary of fluid pressure and velocity comparison of fluid domain

Inlet fluid velocity (m/s)	Fluid flow condition	Maximum pressure of fluid (Pa)	Maximum velocity of fluid (m/s)
0.0003	Laminar	1.42E-04	8.35E-04
0.0040	Transition	1.65E-02	1.00E-02
30.000	Turbulent	1.03E+06	4.80E+01

A similar trend can be observed in Figure 6, where turbulent flow yields significantly higher fluid velocities compared to laminar and transitional flows. In laminar and transitional flows, the maximum fluid velocity only occurs at the upper region of the fixed-free end beam. This phenomenon arises from the transfer of maximum structural deformation, consequently leading to the resultant deflection within the fluid domain. Nonetheless, this principle does not apply in the case of extreme turbulent flow, where the highest fluid velocity is recorded within the backward fluid region of the fixed-free end beam. Contrary to the smooth or layered motion found in laminar and transitional flows, turbulent flow involves irregular fluctuations or mixing within the fluid. In turbulent flow, the fluid experiences drastic magnitude and direction changes due to the interactions with the fixed-free end beam [29].

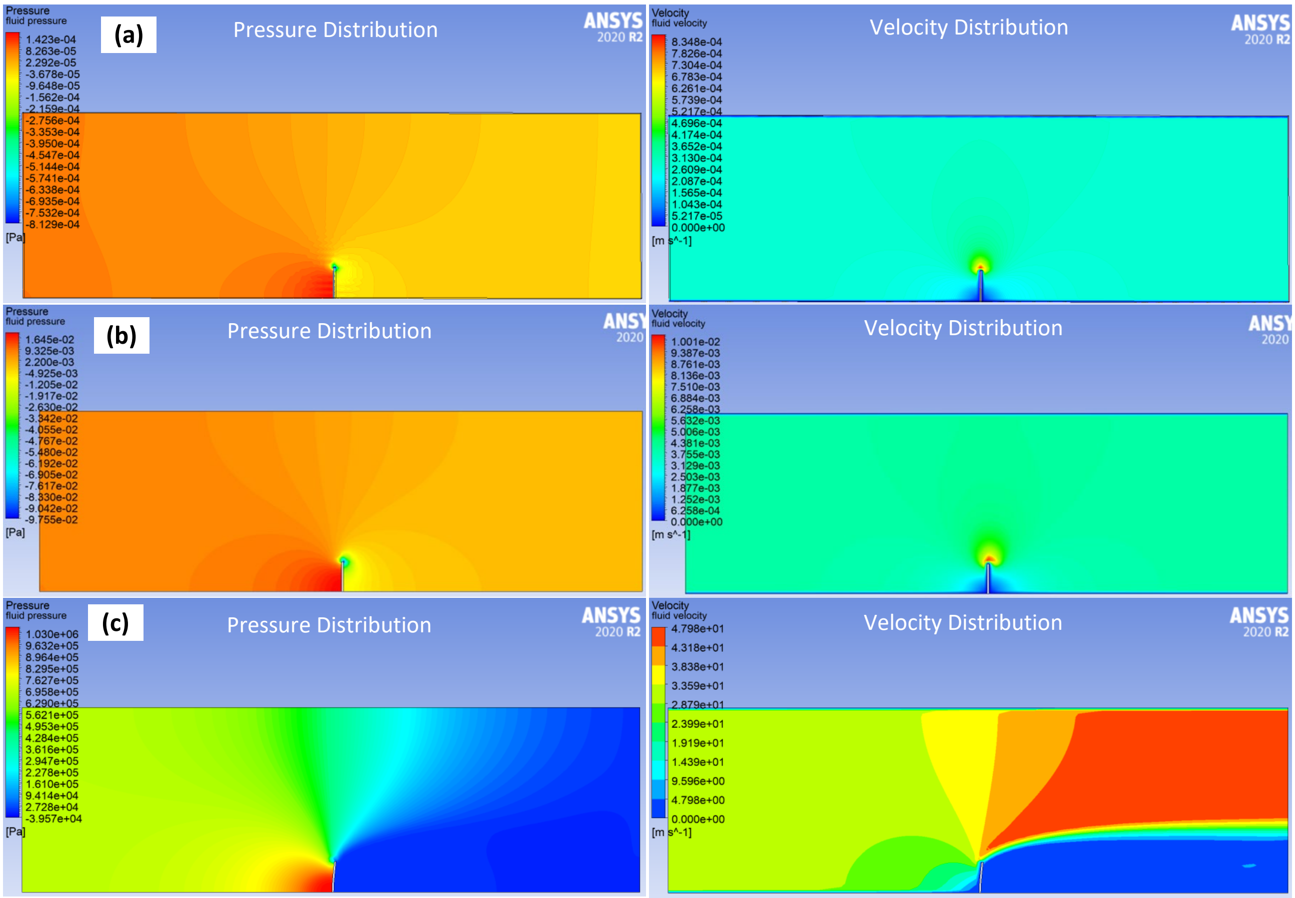

Fig. 6. Pressure and velocity contours for (a) laminar flow and (b) transition flow and (c) turbulent flow

4.2 Static Structural Response of Fixed-Free End Beam

In the analysis of von-Mises stress and total deformation, our focus narrows to the flexible fixed-free end beam, as it is the structural region influenced by the fluid flow. Figure 7 depicts the von-Mises stress distribution and total deformation of the fixed-free end beam under turbulent flow conditions. It was discovered that the deformed fixed-free end beam behaved essentially similarly under three different fluid flow conditions and had the same stress spectrum, as shown in Figure 7(a). Notably, a higher stress concentration is observed in proximity to the fixed end of the beam, with a gradual decrease towards the beam's free edge. To visualize this result, Figure 7(b) illustrates an example of the displacement distribution across the fixed-free end beam model under turbulent flow. This uniformity demonstrates that the stress distribution and structural response are primarily governed by the fluid flow dynamics, with consistent patterns observed across different flow regimes.

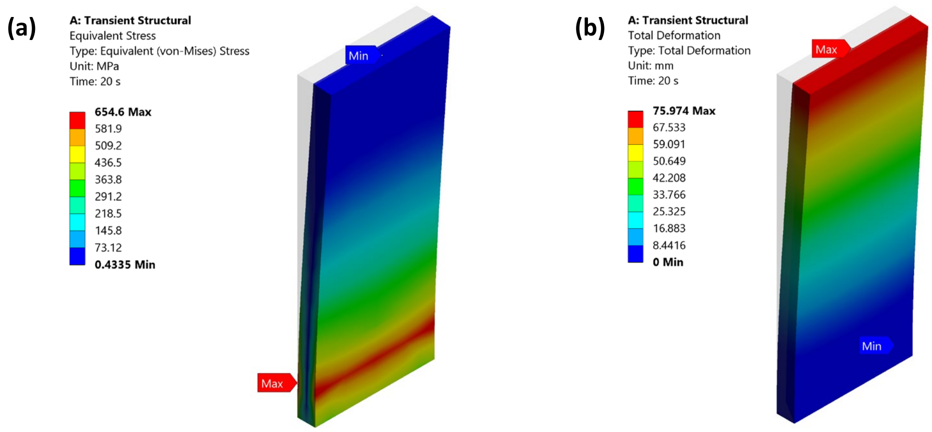

Fig. 7. (a) Equivalent von-Mises stress under turbulent flow (b) Total deformation of fixed-free end beam under turbulent flow

Meanwhile, Table 5 outlines the maximum von-Mises stress and total deformation of fixed-free end beams under laminar, transition and turbulent flow. The simulation data clearly highlights that the highest stress magnitude of 655 MPa and total deformation of 76 mm occurs under the turbulent flow. Conversely, the least pronounced effects are observed in laminar flow. The consistency between our findings and prior research further substantiates the body of work dedicated to optimizing beam characteristics for the reduction of lift and vertical displacement [30].

Table 5
Summary of von-Mises stress and deformation comparison in fixed-free end beam

Inlet fluid velocity (m/s)	Fluid flow condition	Max displacement (m)	Max von-Mises stress (Pa)
0.0003	Laminar	3.76E-11	2.87E-01
0.0040	Transition	4.86E-09	3.81E+01
30.000	Turbulent	7.60E-02	6.55E+08

4.3 Dynamic Characteristics of Fixed-Free End Beam

In this investigation, six natural frequencies of the fixed-free end beams were obtained using both the simulation software platforms, as previously mentioned. Remarkably, these natural frequencies demonstrate consistent results regardless of the different flow regimes. Table 6 presents a comparison of natural frequencies and their percentage differences obtained from ANSYS and Solidworks. Although both software uses identical geometry models and boundary conditions, small percentage differences ranging from 0.14% to 1.42% are observed in the calculated natural frequencies. It is conceivable that these differences are due to the variations in meshing elements and sizes between the ANSYS and the SolidWorks simulation [31]. Figure 8 presents the summary of the mode shapes simulation results in ANSYS and SolidWorks.

Table 6
Summary of the natural frequencies in both simulation software

Mode	ANSYS	SolidWorks	Percentage difference (%)
1st	50.7	50.3	0.88
2nd	245.8	243.7	0.84
3rd	295.7	295.2	0.14
4th	311.9	308.3	1.14
5th	775.9	768.7	0.93
6th	855.4	843.3	1.42

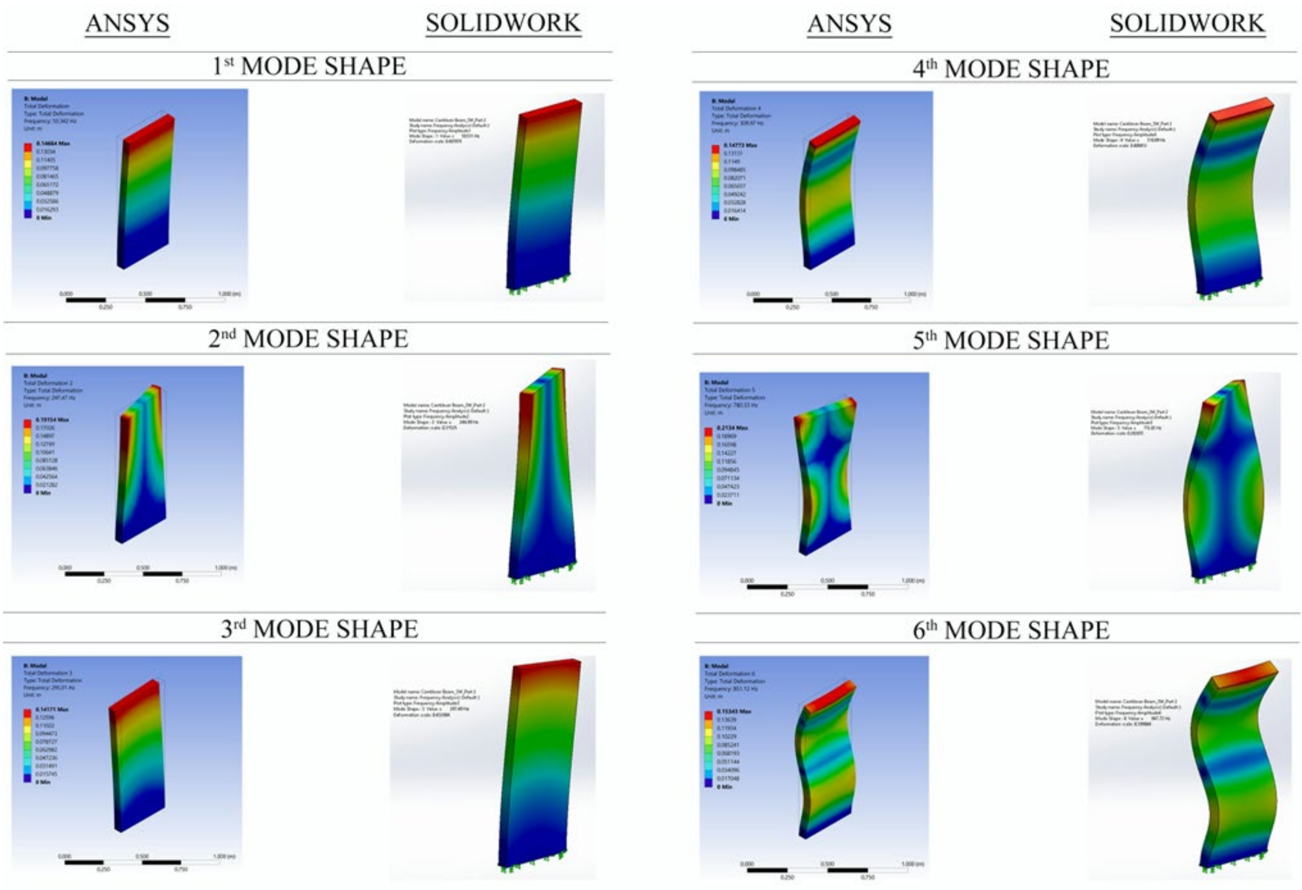

Fig. 8. Mode shapes of fixed-free end beam obtained by ANSYS and SolidWorks simulation

Furthermore, the exploration of the structural response is important to ensure that the response of the system to harmonic excitation in a certain frequency range is examined. Given that the first mode typically represents the highest loads in a structure [32], a range of harmonic frequency spanning from 0 Hz to 100 Hz is chosen for all fluid flow conditions, which accommodates the first natural frequency of the fixed-free end beam of 50.7 Hz. The results of the harmonic response analysis are encapsulated in Figure 9, illustrating the outcomes for three distinct fluid cases: laminar, transient, and turbulent flows.

It is evident from Figure 9 that all these flow conditions show a peak at approximately 50.5 Hz. As expected, the largest amplitude is seen in turbulent flow, surpassing the amplitudes recorded for laminar and transitional flows. This trend can be attributed to the increased fluid velocity and amplified pressure, leading to more pronounced deformation within the structural model.

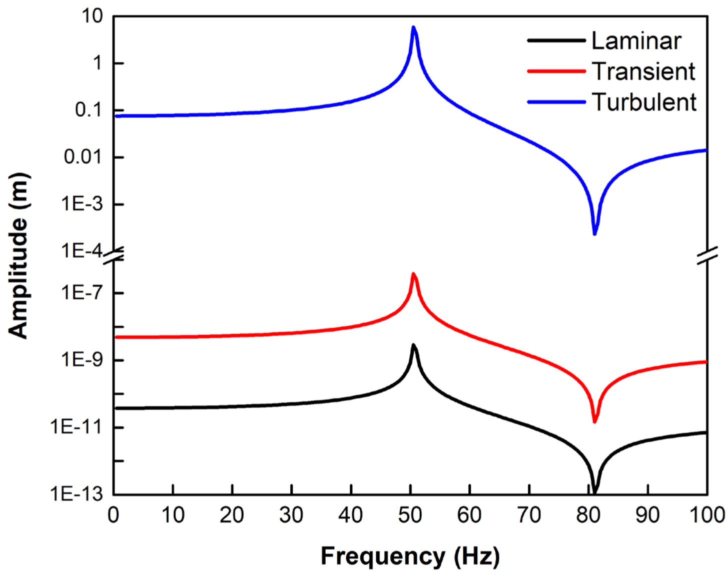

Fig. 9. Displacement over frequency/ Frequency spectrum

5. Conclusions

This investigation set out to present the two-way fluid-structure interaction of the fixed-free end beam and the different inlet fluid flow velocities by the application of simulation software ANSYS. The findings clearly indicate that higher the inlet fluid velocities, the greater the resultant deformation from fluid towards the structural model. The tip of the fixed-free beam experienced the relatively higher velocity and total deformation but with a relatively smaller pressure distribution. These simulations confirmed that turbulent flow experienced the largest pressure distribution while the laminar flow encountered the smallest pressure deflection from the structure. Also identified in the fluid velocity distribution, the maximum resultant velocity is implemented at the tip of the fixed-free end beam for laminar and transition flow cases but not for turbulent flow. The most obvious finding to emerge from this study is that the turbulent fluid flow undergoes an extreme fluid magnitude and direction changes after interrupting by the fixed-free end beam. The natural frequencies and mode shapes of fixed-free end beam were determined using in ANSYS, in which later validated by the SolidWorks simulation. The most obvious finding to emerge from this investigation is that harmonic response outcomes reveal the amplitude of frequency response under turbulent flow is comparatively much higher compared to laminar and transition flow in the same natural frequency region.

The insights gained from this study may be of assistance to understand differential condition flows on fixed-free end beams deflect to different frequencies responses. Further research could also be conducted to determine the effectiveness of different types of fluid density for analyzing different behaviour of fluid-structure interaction of fixed-free end beam in future.

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