E-ISSN 2581 – 7957
P-ISSN 2277 – 3916
CVR Journal of Science and Technology, Volume 27, December 2024
DOI: 10.32377/cvrjst2715

Numerical Analysis of Vibration Behaviour in a Fluid-Structure Interaction Cantilevered Thin Aluminium Plate

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Abstract: **This study uses a simulation approach to replicate and validate the modal characteristics of fluid-solid coupling on a cantilever aluminum plate. Utilizing finite element analysis (FEA), the natural frequencies and vibration modes were investigated under varying fluid conditions. Results closely matched those found in previous simulation studies, confirming the effectiveness of the simulation-based approach for understanding fluid-solid interactions. This work highlights the potential of numerical simulations as a reliable tool in analyzing vibration characteristics, offering valuable insights for engineering applications where fluid-structure interactions are significant.**

Index Terms: modal characteristics, fluid-solid coupling.

I. Introduction

Fluid-solid coupling phenomena play a critical role in various engineering disciplines, including aerospace [3], marine [2], and mechanical systems [4]. In these fields, aircraft wings, ship hulls, and underwater pipelines often interact with surrounding fluids [5], significantly affecting their vibrational behavior. When a structure is fully or partially submerged, its natural frequencies and mode shapes are altered due to the fluid's additional mass, damping, and pressure. This added mass effectively increases the inertia of the structure, while the fluid's viscosity introduces damping forces that dissipate vibrational energy. As a result, the structure's natural frequencies typically decrease, and the vibrational modes are modified compared to a dry (air) environment. These fluid-induced effects are significant in applications where precision and stability are crucial, such as in turbine blades or submarines, where changes in vibration characteristics can lead to performance degradation or failure.

In this study, we aim to replicate the findings of a published experimental modal analysis [1] of a cantilevered thin aluminum plate subjected to fluid-solid coupling, specifically in water. Using finite element simulations, we explore whether numerical methods alone can accurately capture the complex interactions between the structure and the surrounding fluid. The primary focus is on understanding how the fluid alters the natural frequencies and vibration modes of the plate. By comparing the simulation results with the experimental data from the reference study, we assess the validity of using simulations to model fluid-structure interactions. This approach provides insights into the impact of fluid on structural dynamics. It highlights the potential of simulations as a cost-effective and efficient alternative to experimental testing in fluid-solid coupling scenarios.

Fluid solid coupling phenomenon can be explained mathematically in the following forms to understand the physics behind the simulations.

1. Added Mass Effect

When a cantilever beam vibrates in air, the surrounding medium (air) has a low density and negligible influence on the beam's motion. However, when the beam is submerged in water (a denser medium), it displaces a certain volume of water during oscillation. The surrounding water provides additional resistance to the beam's motion, effectively increasing the total mass that needs to be moved. This phenomenon is known as the “added mass effect”.

Mathematical Representation:

The natural frequency (f_n) of a cantilever beam in vacuum (or air) is given by:

$$f_{n,air} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where:
- k is the stiffness of the beam,
- m is the mass of the beam.

When the beam is submerged in water, an “added mass” m must be considered, which modifies the total effective mass of the system. The new effective mass m_{eff} becomes:

$$m_{eff} = m + m_{added}$$

The added mass depends on the geometry of the beam and the density of the surrounding fluid. It is often proportional to the volume of water displaced by the vibrating beam.

The natural frequency in water is then given by:

$$f_{n,water} = \frac{1}{2\pi}\sqrt{\frac{k}{m + m_{added}}}$$

Since m_{added} is positive, $f_{n,water}$ will be lower than $f_{n,air}$, reflecting the decrease in natural frequency.

Received on 17-09-2024, Revised on 17-10-2024, Accepted on 16-11-2024.

CVR Journal of Science and Technology, Volume 27, December 2024
DOI: 10.32377/cvrjst2715

This clearly shows how the surrounding water increases the effective mass, decreasing the natural frequency.

2 Damping Effect.

Damping refers to the dissipation of vibrational energy, which is higher in water due to its higher viscosity and density compared to air. In water, the beam experiences more drag forces and resistance to motion, resulting in energy loss during oscillation.

Damping and Frequency:

Damping itself primarily affects the amplitude of the vibration rather than the natural frequency, but it can still play a role in broadening the resonance peak and reducing the quality factor Q. The equation for a damped system is given by:

$$f_d = f_n\sqrt{1-\zeta^2}$$

where:
- f_d is the damped natural frequency,
- f_n is the undamped natural frequency,
- ζ is the damping ratio.

In most practical cases, ζ is small (i.e., $\zeta^2 \ll 1$), so the shift in frequency due to damping is negligible. However, increased damping in water results in reduced amplitude and faster energy dissipation, affecting the beam's vibrational behavior.

3. Fluid-Structure Interaction

The fluid-structure interaction refers to the interaction forces between the vibrating beam and the surrounding water. When the beam oscillates, it causes the fluid to move, which in turn exerts pressure forces on the beam. This interaction introduces additional forces and modifies the dynamic response of the beam.

Coupled Fluid-Structure Dynamics:

The beam's motion in water is governed by a coupled set of equations that consider both the structural mechanics of the beam and the fluid flow around it. The equations of motion for the beam, including the interaction with the fluid, can be written as:

$$m_{eff}\ddot{u}(t) + c_{fluid}\dot{u}(t) + ku(t) = F_{fluid}(t)$$

where:
- $\ddot{u}(t)$ is the acceleration of the beam,
- $\dot{u}(t)$ is the velocity of the beam,
- $u(t)$ is the displacement of the beam,
- c_{fluid} is the fluid damping coefficient,
- $F_{fluid}(t)$ is the force exerted by the fluid.

This interaction force $F_{fluid}(t)$ depends on the fluid's pressure and shear forces on the beam's surface and is influenced by the beam's velocity and acceleration. The presence of these forces further modifies the beam's vibrational characteristics.

The overall reduction in the natural frequency of a cantilever beam immersed in water compared to air is primarily due to the added mass effect.

II. METHODOLOGY

A. Simulation setup

The simulation was conducted using finite element software, ANSYS. The cantilever beam modeled was an aluminum plate with dimensions identical to those in the reference study [1]: 180 mm × 40 mm × 2 mm but the length of the beam is reduced to 150mm as one end of the beam is fixed with a bench vice up to 30mm of its length. The material properties used for aluminum are as follows (Table 1):

TABLE-I.
MATERIAL PROPERTIES OF ALUMINUM

Property/Material	Aluminum 8011 Alloy
Youngs modulus	7.1e10 Pa
Poisson's ratio	0.33
Density	2770 kg/m^3

The fluid medium was modeled as water with dimensions 120 mm×140 mm×180 mm, with acoustic properties such as sound speed and density integrated into the simulation environment. The simulation was divided into two primary cases:

1. Dry Mode: Simulating the structure in air.

In the dry mode, the fluid medium is suppressed, and the modal analysis is carried out in an air medium as shown in Fig.1. The excited cantilever beam provides us with modal frequencies. Figures show the first five mode shapes of the beam in the air.

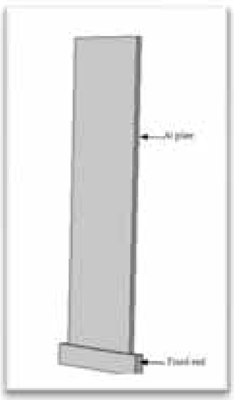


Figure 1. Al plate fixed at one end in air medium

2. Wet Mode: Simulating the fully submerged structure.

In this case, the aluminum plate is submerged in water and fixed on one end. The water ambiance is provided as a parallelopiped model as shown in Fig.2. One of the surfaces is considered a free surface as the water is not bound by any surface. The boundary conditions offered here are like those in the dry mode. Due to the viscosity and weight of the water, an additional mass is added to the plate assembly, thus reducing the natural frequencies of the plate, which is considered the damping effect. The reduced frequencies and their corresponding mode numbers are highlighted in Table 2.

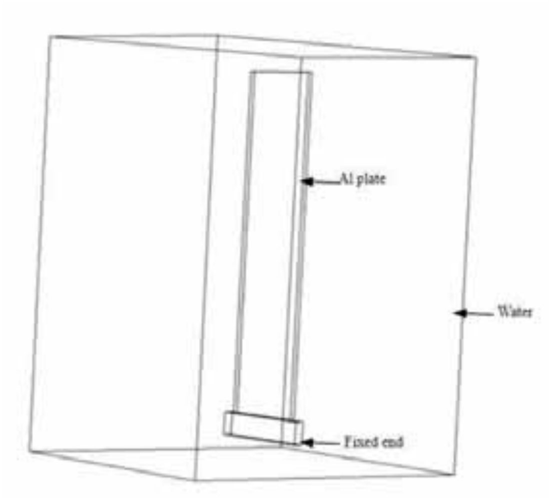


Figure 2. Al plate fixed at one end in air medium

B. *Finite Element Model*

The fluid-structure interaction (FSI) was addressed using acoustic-fluid elements in the simulation. The cantilever plate was fixed at one end, while the fluid domain was modeled as a rectangular enclosure around the plate, with a free surface representing the air-water interface. The finite element model consisted of a fine mesh with hexahedral elements for the structure and tetrahedral elements for the fluid domain. The meshing sizes (plate-10mm and fluid are-20mm) are slightly varied from that of the reference due to limitations in the FEA tool.

TABLE-II.

MODE NUMBERS AND CORRESPONDING FREQUENCIES IN AIR AND WATER

Mode	*Air [1]*	*Air (current work)*	*% deviation*	*Water [1]*	*Water (current work)*	*% deviation*
1	73.6	74.5	1.2	30.5	31.69	3.9
2	460.1	468.6	1.8	199.1	205.28	3.1
3	550.58	556.1	1.0	306.5	317.14	3.5
4	1290	1302.6	0.9	592.0	610.1	3.1
5	1705	1723.5	1.08	960.5	994.15	3.5
6	2532.1	2583.6	2.0	1236.9	1245.5	0.7
7	3010.4	3057.9	1.6	1729.6	1760.2	1.8
8	4186	4244.4	1.4	2162.5	2205.3	2.0
9	4545.7	4582.8	0.8	2641.9	2685.6	1.7
10	6215.7	6222.1	0.1	3381.2	3391.7	0.3
11	6371.3	6348.2	-0.36	3833.6	3855.5	0.6
12	6818.5	6832	0.2	4333.7	4339.5	0.1
13	7486.7	7497	0.1	4767	4792.1	0.5

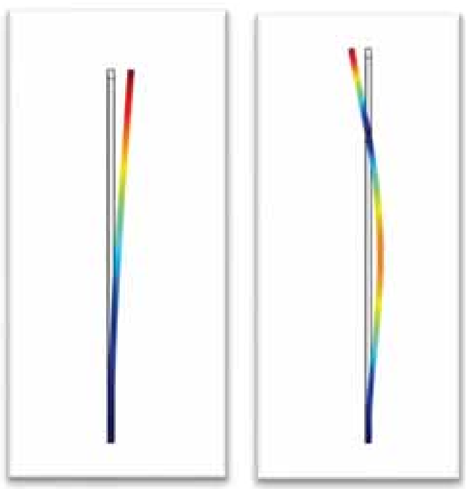
III. Results and Discussion

A. *Natural frequencies*

The natural frequencies for both dry and wet conditions were calculated using modal analysis. Table 2 presents the first 13 modes of vibration for the cantilever aluminum plate in air and water. The simulation results aligned well with the previously published simulation results [1]. It is observed that the reduction of the frequency value corresponding mode does not affect its mode shape. This proves that the mode shape of a structure is not confined to a single frequency.

B. *Mode shapes*

The first few mode shapes were analyzed, including pure bending and combined bending-torsion modes. It was observed that fluid immersion significantly reduced natural frequency but had little effect on the general mode shapes. Like the simulation findings, the fluid-structure interface increased the rate of frequency drop, particularly in higher-order modes. The mode shapes in the bending and torsion in both dry and wet conditions of the plate are shown in Fig.3 and Fig.4.



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DOI: 10.32377/cvrjst2715

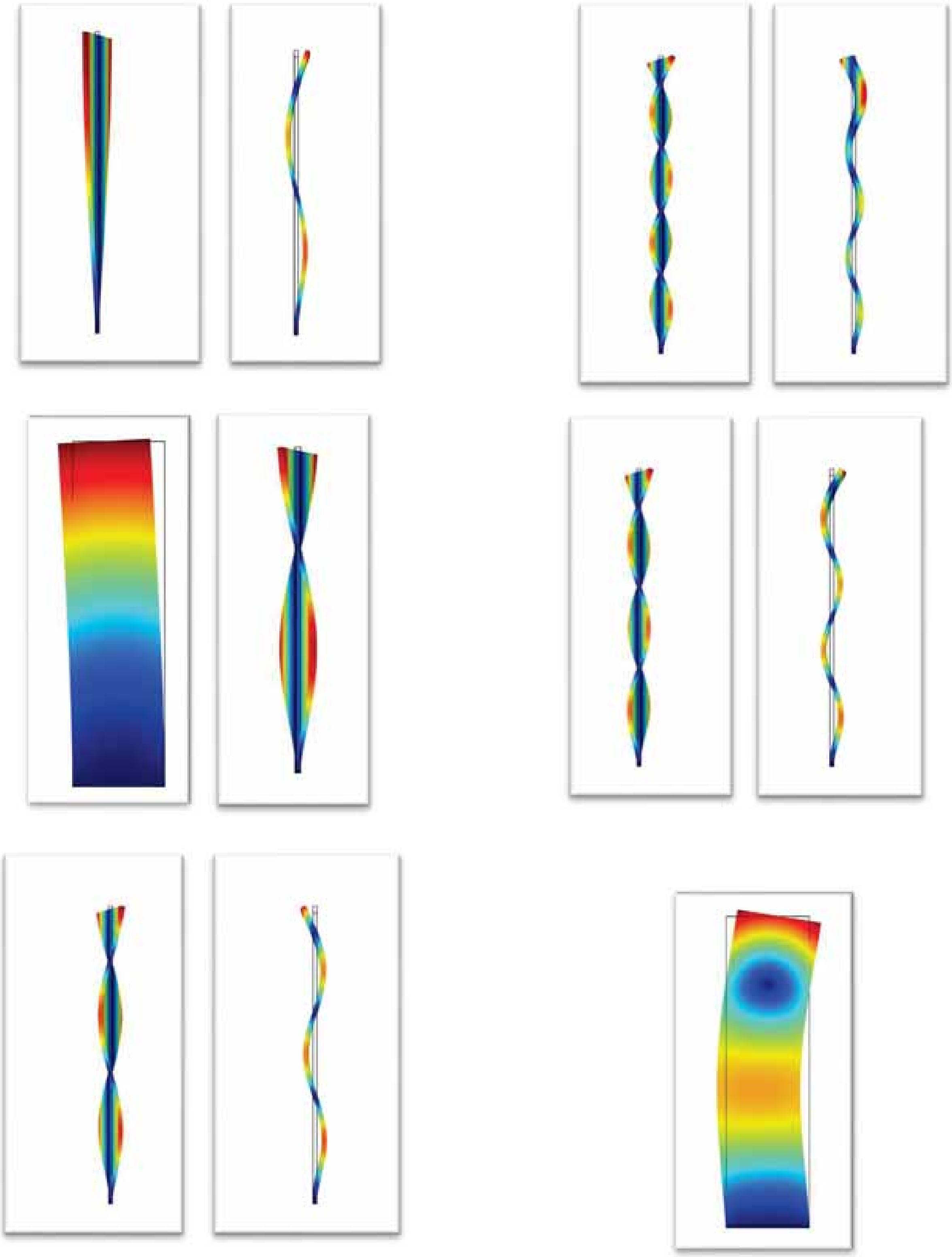
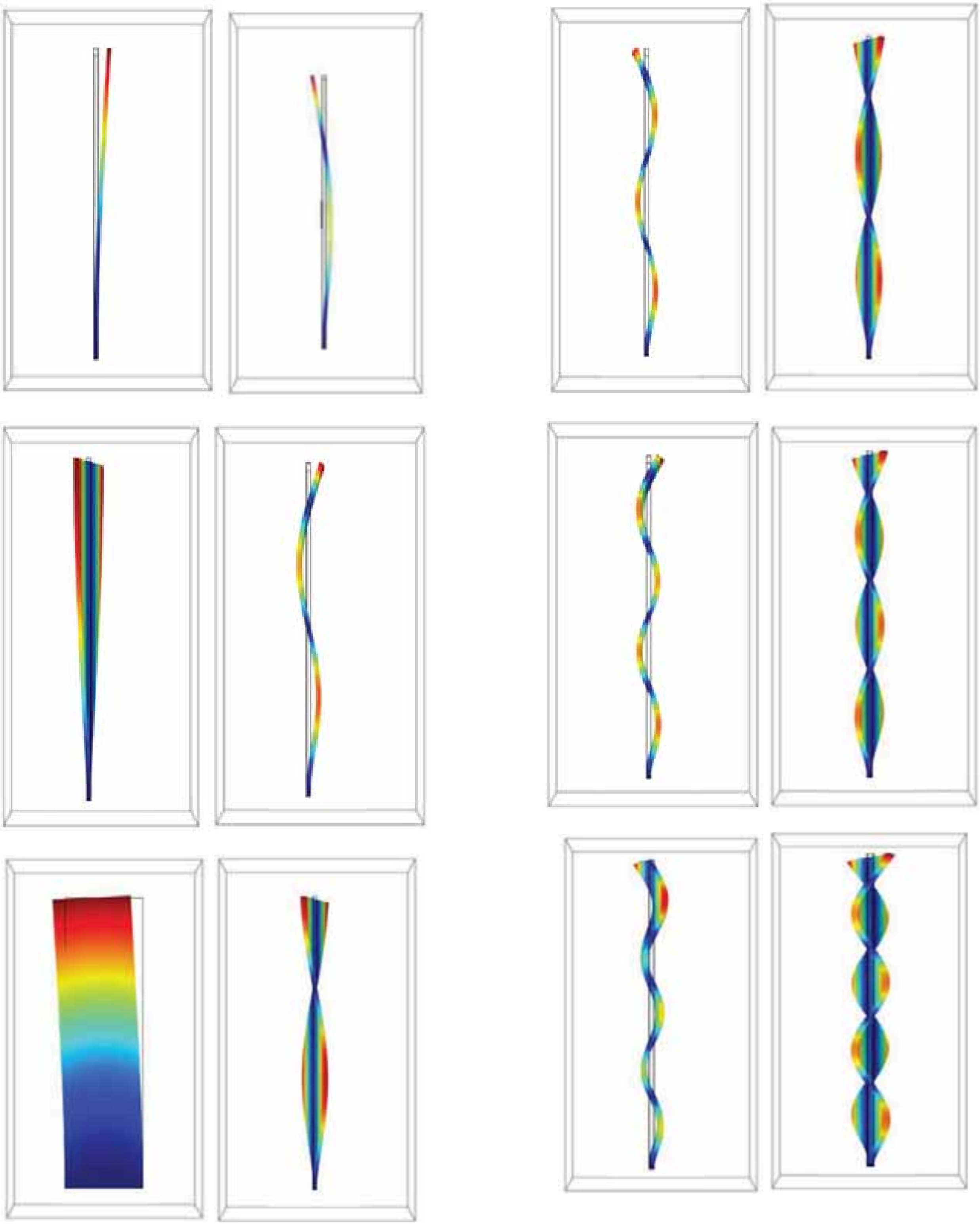


Figure 3. Mode shapes (1-13) of Al plate in air-bending and torsion



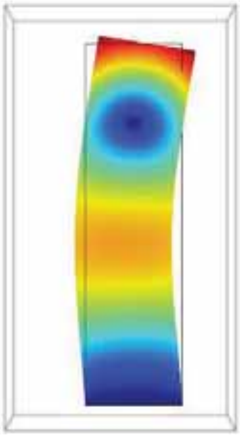


Figure 4. Mode shapes (1-13) of Al plate in water- bending and torsion

IV. Conclusions

This study successfully replicated the vibration characteristics of a cantilever aluminum plate in a fluid (water) using only finite element simulations. The results closely matched experimental findings, demonstrating that simulations can serve as an effective method for studying fluid-solid coupling phenomena. The study also highlighted the significant role of additional mass and damping induced by the surrounding fluid in reducing the natural frequency of the structure. In future work, simulations could be further refined to account for complex fluid dynamics or non-linear effects.

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