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Poster Session

Thu. Jul 18, 2024 4:30 PM - 6:30 PM Room P

[PO-02] Physics-informed neural networks for fluid-induced excitation

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Keywords: fluid structure interaction, flutter, physics informed neural networks

Physics-informed neural networks for fluid-induced excitation

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1 Introduction

The dynamic interplay between fluid flow and structural integrity forms the cornerstone of fluid-structure interaction (FSI) analysis, a domain critical to advancing our understanding of many natural and engineered systems. Among the myriad challenges in FSI, the phenomenon of flutter in flexible structures under fluid flow stands out due to its complexity and significant implications in various engineering applications, from aerospace to civil engineering.

Flutter, a potentially destabilizing oscillation that can arise when a structure interacts with fluid flow, has been a subject of extensive research. Traditional computational methods, such as finite element analysis and computational fluid dynamics, have provided substantial insights into these interactions. However, these approaches often encounter limitations when dealing with the nonlinear and dynamic nature of flutter in flexible structures. The challenges are magnified by the need to accurately model the intricate coupling between the structure's inherent flexibility and the surrounding fluid's dynamic forces.

Physics-Informed Neural Networks (PINNs) have emerged as a groundbreaking development in computational science, gaining significant attention for their adaptability in handling a variety of problem setups. This includes solving forward problems to determine solution curves of integral and differential equations, and tackling inverse problems for data-driven discovery under established physical laws. Since the inception of PINNs, which ingeniously integrate the residuals of partial differential equations (PDEs) into the neural network's loss function, there have been substantial advancements in enhancing PINNs through novel neural network architectures, optimized loss functions, strategic training methodologies, and practical implementation techniques.

This study introduces a pioneering application of PINNs in the context of FSI, focusing on the fluid-flow-induced flutter of flexible cylinders. The research leverages the power of PINNs to decipher and predict the flutter behavior of cylindrical structures subjected to fluid flow, an area of significant relevance in both academic research and industrial applications. By marrying advanced computational techniques with established theories of fluid dynamics and structural mechanics, this study aims to bridge the gaps in our current understanding of flutter phenomena. The application of PINNs in this context represents not just an incremental advancement, but a significant leap forward in the realms of computational fluid dynamics and structural engineering, promising new insights and improved predictive capabilities in the complex world of fluid-structure interactions.

2 Problem Statement

The fundamental problem addressed in this research is the accurate modeling and prediction of flutter in flexible structures, specifically cylindrical beams, under the influence of fluid flow. Traditional models often fall short in capturing the intricate dynamics of this interaction due to the complex nature of the coupled partial differential equations governing fluid and structural behavior. The Euler-Bernoulli beam theory, while robust for structural dynamics, requires integration with fluid dynamic pressure considerations for a comprehensive analysis, as suggested by Lighthill's slender body theory [1].

$$\mu \frac{\partial^2 \omega(x,t)}{\partial t^2} + B \frac{\partial^4 \omega(x,t)}{\partial x^4} = q(x,t)$$

The primary focus of this research is the detailed analysis of the fluid-induced flutter of a slender cantilevered beam. The model considers the transverse load $q(x,t)$ originating from the fluid's interaction with the beam structure. Drawing upon Lighthill's elongated body theory, the aerodynamic force on the slender cantilevered beam (with length L much greater than width l) is modeled. This approach takes into account the added mass m_a and the transverse fluid velocity v with the fluid density ρ_f playing a crucial role. The transverse load $q(x,t)$ is formulated as a reaction to the fluid momentum's rate of change, encapsulated in the second-order differential equation:

$$q(x,t) = -\frac{\pi \rho_f l^2}{4}\left(\frac{\partial^2 \omega}{\partial t^2} + 2U \frac{\partial^2 \omega}{\partial x\, \partial t} + U^2 \frac{\partial^2 \omega}{\partial x^2}\right).$$

This equation, alongside the fourth-order differential equation from dynamic beam bending theory, describes the coupled fluid-structure system. The challenge lies in resolving these high-order differential equations, crucial for understanding the complex flutter behavior under various conditions, including axial flows and free oscillation in different beam configurations. The proposed PINN model addresses these challenges, showcasing its potential in enhancing the predictability and understanding of fluid-structure interactions.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. RS-2023-00279929)

References

[1] Lighthill, M.J. (1970). Aquatic animal propulsion of high hydromechanical efficiency. J. Fluid Mech, 44(2), 265-301.