"Morphing Boundaries: A Multiscale Framework for Fluid-Structure Interaction in Adaptive Aeroelastic Systems"

Shantanu Dutta[1] Sandip Majumder[2]

[1]Sanaka educational trust group of institutions

[2]Research scholar NIT Durgapur

Fluid-Structure Interaction (FSI) lies at the heart of numerous engineering systems, from aerospace vehicles and wind turbines to biomedical devices and civil infrastructure. As the demand for adaptive, resilient, and high-performance structures grows, traditional FSI models—often limited by scale separation and rigid boundary assumptions—struggle to capture the dynamic complexity of real-world phenomena. This paper introduces a novel multiscale framework for modeling and simulating FSI in **adaptive aeroelastic systems**, where structural boundaries evolve in response to fluid forces, and vice versa.

Our approach integrates **nonlinear structural dynamics**, **unsteady fluid mechanics**, and **data-driven morphing algorithms** to simulate the coupled behavior of flexible surfaces interacting with turbulent flows. At the core of the framework is a **hybrid solver architecture** that combines high-fidelity computational fluid dynamics (CFD) with reduced-order structural models, enabling efficient yet accurate simulations across scales. The solver is enhanced with **machine-learned surrogate models** trained on experimental data to predict boundary deformations and flow separation events in real time.

We validate the framework using wind tunnel experiments on a morphing wing prototype with embedded sensors and actuators. The results demonstrate significant improvements in lift-to-drag ratio, vibration suppression, and flow control compared to conventional rigid designs. Furthermore, we explore the implications of this framework for **bioinspired flight**, **energy harvesting**, and **next-generation UAVs**, where adaptability and responsiveness are critical.

This work pushes the boundaries of FSI research by proposing a **fluid-structure co-evolution paradigm**, where the structure not only reacts to the fluid but also proactively reshapes the flow field. The proposed methodology opens new avenues for designing intelligent systems that learn, adapt, and optimize their performance in complex environments.

Keywords:

Fluid-Structure Interaction (FSI); Adaptive Aeroelasticity; Morphing Structures; Multiscale Modeling; Hybrid Solver Architecture; Machine Learning in FSI; Reduced-Order Modeling; Bioinspired Design;Flow Control; Smart Materials and Actuators