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Machine Learning-Enhanced Light-Field Fluid-Structure Interaction Diagnostics

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Abstract

We introduce a novel experimental methodology for fluid-structure interaction (FSI) diagnostics that employs a single light field camera to simultaneously capture time-resolved, three-dimensional, three-component (3D3C) velocity fields and structural deformations of a flexible structure. Light field cameras encode both spatial and angular information of light rays, enabling 3D scene reconstruction from a single image. Leveraging recent advances in high-speed light field imaging, we establish a single-camera approach for FSI diagnostics, focusing on capturing interactions between leaflets and the surrounding flow field in a low-optical-access heart valve experiment.

Traditional FSI diagnostics treat fluid and structural phases independently, limiting the accuracy of interface measurements. To address this, we propose a framework that integrates physics-informed neural networks (PINNs) to enhance velocity field reconstructions by incorporating structural position data. Using a plenoptic imaging system, we independently reconstruct fluid and structural phases. The PINN then combines flow measurements with governing equations and structural positions as constraints, providing refined flow-field diagnostics at the fluid-structure interface.

The current framework is one-way coupled, focusing on enhancing flow diagnostics based on structural information. Future work aims to extend this methodology to a two-way coupling for comprehensive FSI analysis. The performance of the proposed approach is validated using synthetic data generated from coupled FSI computational simulations of a flexible membrane, while experimental demonstrations are planned in a heart valve setup. This integrated, single-camera-based diagnostic framework offers a new way of FSI diagnostics in complex and constrained setups.

Keywords: 3D reconstruction, plenoptic camera, physics informed neural network, experimental methods, flexible membrane