A Novel Low-Cost Zero Mean-Flow Chamber Design and Physics-Informed Neural Network for Astrophysical and Environmental Turbulence Applications

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Turbulence is a natural phenomenon that serves as an underlying principle for many other fields, ranging from astrophysical studies of star formation to climate change modeling. Due to its complex nature, understanding turbulence remains a classical physics problem. The goal of this project is to design, build, and test a novel zero mean-flow chamber for statistical turbulence measurements as well as implement a Physics-Informed Neural Network (PINN) to improve turbulence modeling. It is hypothesized that the PINN will predict the Reynolds stress term more accurately than traditional NLEVM and LEVM methods. Experimental apparatuses with zero mean flow are crucial to capturing pure turbulence characteristics and verifying statistical theories. The chamber utilizes 6 symmetrically distributed actuators and circular disk extensions to create both isotropic and anisotropic conditions. A low-cost Particle Image Velocimetry (PIV) system is developed to characterize turbulence of up to Taylor microscale Reynolds number 152. A PINN that reconstructs the Reynolds stress tensor and enforces realizability constraints was applied to the closure problem. NASA’s 2D converging-diverging channel flow dataset was used. The neural network incorporates a physics-informed loss function, invariant feature sets, and a hyperparameter sensitivity study. The chamber design achieved a near-zero mean-flow condition with less than 1.5% error. The PINN demonstrated 97% accuracy for Reynolds stress predictions when compared to ground truth. These achievements emphasize the role that the PINN and novel chamber system have for the future of turbulence physics, specifically in astrophysical and environmental applications.

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