Wind Energy Harvesting based on Flow-induced Vibrations and Community Acceptance

–Year 1 (2022.06 – 2023.04) Progress Summary

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1 Overview of the progress

The proposed research is motivated to 1) design durable and eco-friendly flow-induced vibration wind energy harvesters (FIV-WEHs), 2) quantify the impacts of FIV-WEHs on local residential environments, and 3) analyze community acceptance including acceptance-related factors. This interdisciplinary research involves energy and mechanical engineering, environmental sustainability, and community engagement, and requires a thorough understanding of fluid-structure interactions (FSI) and fluid dynamics. However, the traditional computational fluid dynamics based numerical solvers and experiments can be expensive for simulating high-dimensional and multi-physics problems. The ever-increasing availability of data and rapid advancement in deep learning techniques open up new avenues to address these challenges. The focus of the first year's research is on **developing a hybrid neural differentiable model** seamlessly leveraging numerical algorithms and deep neural networks for simulating FSI and environmental fluid dynamics. The model can efficiently simulate FIV and turbulence, which is a crucial tool for designing/optimizing FIV-WEHs and evaluating impacts on surrounding environments. Another objective is to **integrate the proposed technology with environmental and energy policies**, which will promote the practical utilization of renewable energy locally and internationally. To achieve this goal, I collaborated with Prof. Sisi Meng to co-advise Izzy Cheng, a senior undergraduate student at Notre Dame. Using qualitative research methods, the project aims to gain an understanding of the impacts and challenges of the "Carbon Neutral 2025 - South Bend's Climate Action Plan", with a particular focus on sustainability and renewable energy. Furthermore, with the support of this funding, I have participated in several academic activities. The progress is summarized below.

2 Research findings

2.1 Neural differentiable model for energy harvester

The typical structures of FIV-WEHs can be classified into elastically-supported rigid body and self-supported flexible body. For these two typical cases, we established a differentiable hybrid neural model for efficiently simulating their FSI regimes. By integrating the numerically discretized FSI physics with deep sequential neural networks through differentiable programming, we enabled end-to-end, sequence-to-sequence training of the entire model for long-term model rollouts. The proposed hybrid neural solver exhibits significant superiority in terms of generalizability, robustness, and prediction speed. The speedup can be further improved by 8.3 times for long-term forecasting. The flow patterns, structural responses and energy power can be accurately modeled. The proposed neural solver is well-suited for many applications requiring long-span simulation or repeated model queries, such as design optimization of FIV-WEHs, wind turbines, hydrofoils and etc. The proposed model can also be adopted to other related projects in ND-CCI and ND-Energy. The main results are summarized in Fig. 1.

2.2 Fast solver for simulating environmental fluid dynamics

In order to evaluate the impacts of FIV-WEHs on surrounding environments, an efficient computation and comprehensive insight into the turbulence features around energy harvester devices is critical. We further developed a 3D solver on GPU to simulate the turbulent flow and investigate the environmental fluid dynamics. We used a $Re_\tau = 180$ channel flow as a benchmark to validate the solver. The turbulence statistics and flow structures are shown in Fig. 2, indicating the accuracy of the solver. Meanwhile, the speedup of our solver is 30 times faster than OPEN-FOAM. It holds the potential capability to efficiently estimate the impacts of FIV-WEHs with various parameters on environments. It also holds the potential to model flow of stream and transport of pollutants in many environmental-related researches. I'm conducting more validation cases and preparing the manuscript for this part.

2.3 Qualitative study of the South Bend Climate Action Plan

The development of renewable energy is also influenced by the policy, investment and community acceptance. To gain insights into these factors in the local region near the University of Notre Dame (South Bend, Elkhart), I collaborated with Professor Meng and senior undergraduate student Izzy Cheng to conduct a qualitative research study of South Bend's Climate Action Plan, which aims to achieve carbon neutrality by 2050. Our goal is to understand the impacts and challenges of the Plan at the community level and identify actionable policies regarding renewable energy and sustainability. The preparatory work for this study began in January 2023, during which we reviewed policy documents in South Bend and designed an interview protocol. We have completed six interviews with government officials, community leaders, and ND professors. The final report will be submitted as part of the student's capstone project for the Hesburgh Program in Public Service by the end of May 2023. Professor Meng and I plan to continue this research and aim to produce publishable output in the future.

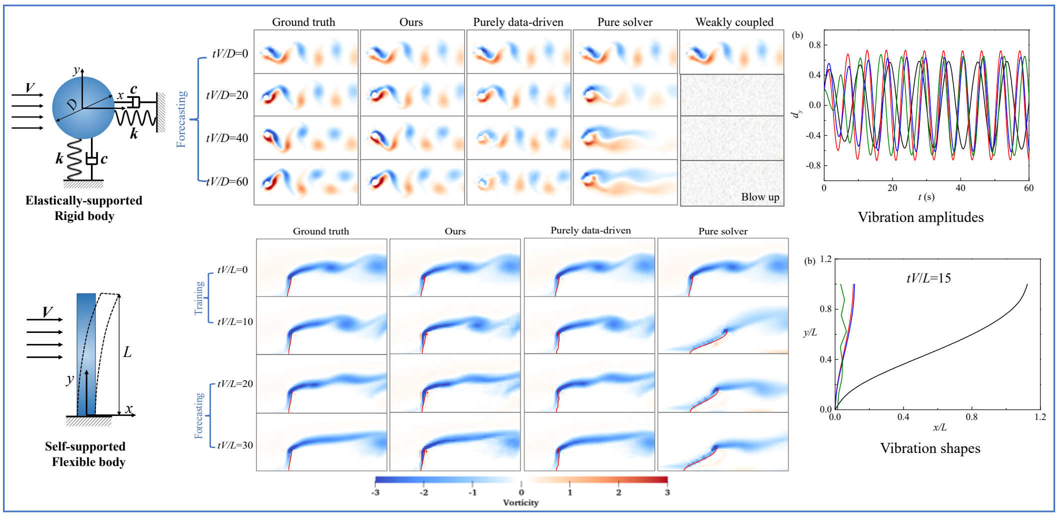

Figure 1: Overview of modeling two typical FSI regimes in FIV-WEHs by the proposed neural model

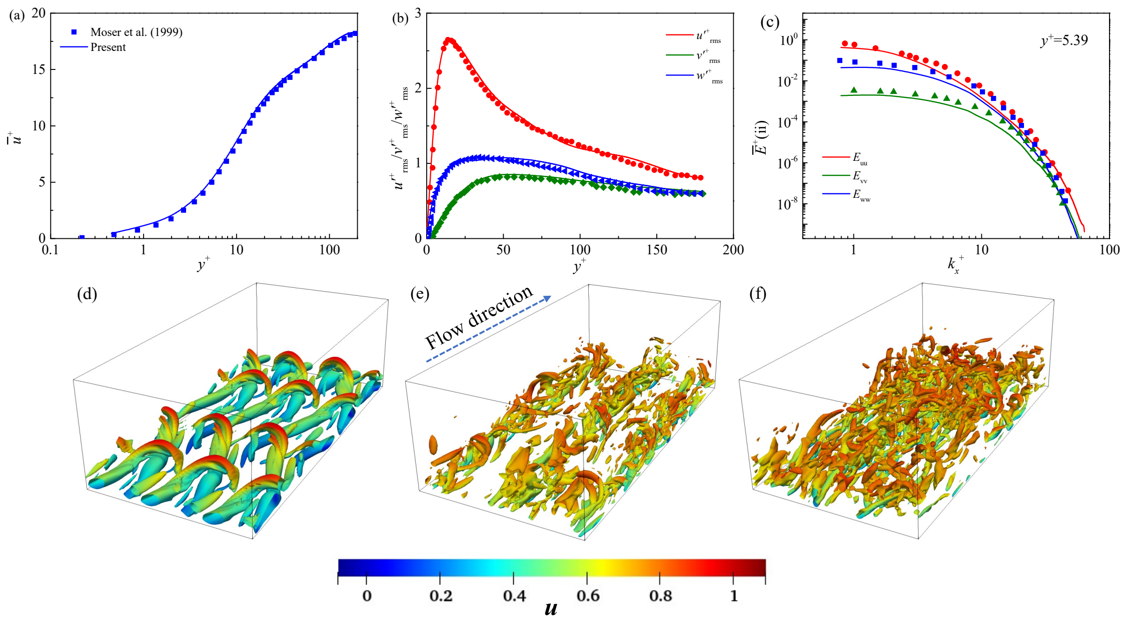

Figure 2: Overview of modeling turbulence features for channel flow at $Re_\tau = 180$

3 Academic achievements and activities

Paper: Based on the above research findings, I have completed one journal manuscript, which is entitled *Differentiable hybrid neural modeling for fluid-structure interaction*. It has been submitted to *Journal of Computational Physics* for reviewing. The preprint can be found at https://arxiv.org/abs/2303.12971.

Conference: I attended two conferences this year supported by the fellowship. I gave an oral presentation to show my preliminary results in ***APS fluid dynamics 2022***. In this conference, I mainly presented the results from the fundamental fluid mechanics sides. I also presented my results in a poster session with application in energy harvesting in ***AGU Fall meeting 2022***, where I discussed with many researchers about the applications of the proposed method, especially for environmental sciences.

Seminar: I gave two talks in FlowPac (organized by Institute for Flow Physics and Control) and ND Energy PDGS seminar (organized by ND Energy) this year.

4 Year 2 plans

In the second year, I will focus on the application of the hybrid neural model on energy harvesting. specifically, I will: (1) apply this model to investigate the FSI mechanism and optimize the design of FIV-WEHs; (2) estimate the environmental impact using this model; (3) collaborate with Professor Meng to explore the socioeconomic and policy implications of my research; (4) attend regional and international conferences, such as 17^{th} USNCCM, APS DFD 2023 to present my research; (5) engage with faculty and students at ND-Energy and the Environmental Change Initiative (ECI) to explore other research and project opportunities in related fields.