【Grant-in-Aid for Scientific Research (S)】

Broad Section C

Title of Project：Creation and implementation of an innovative flow control paradigm utilizing machine learning

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【Purpose and Background of the Research】

Modern fluid mechanics research has a history of more than 100 years. In recent years, large-scale simulations have also helped improve the performance of industrial applications. However, even now, methodologies for flow control and optimization based on an essential understanding of flow phenomena have not been established. In particular, turbulence remains an unsolved problem due to its huge degrees of freedom and strong nonlinearity. Since it is difficult to understand, control or optimize flows with such huge degree of freedom, fluid mechanicians around the world desire to better control and optimize the flow through expressions with a small number of degrees of freedom.

On the other hand, in the third artificial intelligence boom in recent years, the possibility of understanding, controlling, and optimizing the flow using machine learning technology is expected in the field of fluid mechanics as well, and the development of "data-driven fluid mechanics" has already become a major trend all over the world.

Based on this background, we tackled extracting the characteristics of the flow using machine learning in the Grant-in-Aid for Scientific Research (A) in 2018-2020 (No. 18H03758). The purpose of the present research is to extend this and propose a methodology for constructing a new flow control method by utilizing machine learning.

【Research Methods】

As the first step, the convolutional neural network based autoencoder (CNN-AE) is used as the core technology to extract the low-dimensional representation of the flow field, and the sparse regression method is used to derive the dynamical equations including the response to the control input. As shown in Fig. 1, the flow field with control input is low-dimensionalized using CNN-AE, and the governing equations for the low-dimensional latent vector are derived with help of sparse regression. The merit in using CNN-AE is that it is possible to express a complicated flow with a smaller number of modes (or latent variables) compared to the conventional methods, which will facilitate the more efficient application of control and optimization theories.

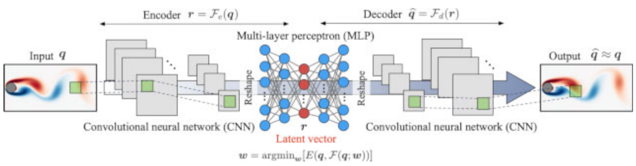

Figure 1 Low-dimensionalization of flow fields by CNN-AE

In the second stage, we will establish a nonlinear model-based control method based on machine learning by applying the modern control theory to the extracted low-dimensional dynamics, whereby we establish a foundation to achieve a novel flow control methodology, verify its control effect using direct numerical simulation (DNS), and attempr to physically understand the complicated flow by performing a physical interpretation of the controlled flow fields including turbulence.

At the final stage, we will propose a practical flow control method based on the results so far. In addition, by conducting experimental demonstrations and integrating the series of research results, we will establish a methodology not only for controlling and optimizing fluid flows but also for understanding a wide range of natural phenomena.

【Expected Research Achievements and Scientific Significance】

Fundamental technology for innovative flow control will greatly contribute to a sustainable society through energy saving and mitigation of environmental load in various industrial applications. Fluid mechanics is a discipline that forms the basis of industrial and social activities. The future efforts toward "carbon neutrality" should also be difficult to realize without further enhancement or evolution of the fluid mechanics. Regarding the creation of a paradigm in fluid mechanics and its surrounding academic fields, we believe that machine learning has the potential to complement the existing mechanics. Our team hopes to strongly promote the foundation development through this research.

【Publications Relevant to the Project】

・ K. Fukami, T. Murata, K. Zhang, and K. Fukagata, "Sparse identification of nonlinear dynamics with low-dimensionalized flow representations," *J. Fluid Mech.* (2021). https://doi.org/10.1017/jfm.2021.697
・ T. Nakamura, K. Fukami, K. Hasegawa, Y. Nabae, and K. Fukagata, "Convolutional neural network and long short-term memory based reduced order surrogate for minimal turbulent channel flow," *Phys. Fluids* **33**, 025116 (2021).
・ T. Murata, K. Fukami, and K. Fukagata, "Nonlinear mode decomposition with convolutional neural networks for fluid dynamics," *J. Fluid Mech.* **882**, A13 (2020).

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https://kflab.jp/en/index.php?21H05007