Physics-Informed Machine Learning for Ocean Wave Fields: Trends, Opportunities, and Challenges

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# Introduction (*Heading 1*)

* Paragraf ke-1

Hydrodynamic merupakan cabang dari fluid mechanic yang mempelajari pergerakan dari fluid dan gaya yang bekerja pada solid bodies immersed in those fluids [1]. Implementasi dari studi bidang hydrodynamics telah dilakukan pada berbagai bidang, baik pada bidang oceanography [2, 3], biomechanics [4], marine engineering [5] serta civil engineering [6]. Dalam mewudjudkan implementasi tersebut, perencanaan melalui pemodelan perlu dilakukan untuk meminimalisir terjadinya error atau biaya yang dikeluarkan pada proses trial dan error. Salah satu teknik pemodelan yang paling banyak digunakan adalah computational fluid dynamics (CFD).

CFD memainkan peranan penting dalam pemodelan dan simulasi numerik pada sistem fluida kompleks di berbagai domain. Pada perkembangannya, CFD telah mampu menyelesaikan persamaan partial differential equation kompleks melalui penyelesaian numerik menggunakan berbagai metod seperti Finite Volume Method (FVM), Finite Element Method (FEM) [7], Finite Difference Method [8] dan Smoothed Particle Hydrodynamic [9]. Namun terdapat permasalahan pada implementasi teknik CFD tradisional, yakni tingginya computational cost yang tinggi untuk model yang berukuran kecil. Tidak hanya itu pengurangan beban computational cost akan berdampak juga pada pengurangan waktu komputasi dengan trade off tingkat akurasi yang di dapatkan [10]. Kemudian, permasalahan scalability dan high dimensionality pada pemodelan CFD juga dapat berdampak pada computational cost serta time computational process [11].

Berbagai pendekatan telah dilakukan untuk menyelesaikan permasalahan tersebut salah satunya adalah melalui data-driven approach [12–16]. Data-driven merupakan pendekatan yang menggunakan data sebagai sumber primer untuk melakukan pemodelan, prediksi atau optimisasi melalui penggunaan teknik statistik ataupun machine learning untuk mengeathui relasi, pola maupun trend dari objek yang ingin di identifikasi. Terdapat banyak sekali metode data-driven yang bertujuan sebagai alternatif dari CFD seperti response surface method [17–21], reduced-order model [22–25] dan salah satu metode yang sedang meningkat perkembangannya, yakni dengan menggunakan pendekatan machine learning [26–29].

Pendekatan menggunakan pendekatan data-driven berbasis machine learning dalam menyelesaikan permasalahan kompleks pada governing equations memiliki keunggulan signifikan ketimbang tradisional CFD method. Keunggulan tersebut terletak pada time processing yang lebih rendah, bahkan hingga 250 kali cepat ketimbang metode CFD tradisional [16]. Hal ini membuat penelitian terkait CFD dengan metode data-driven berbasis machine learning mengalami peningkatan di 10 tahun terakhir yang ditunjukkan pada Fig. 1. Walaupun pendekatan ini menawarkan keunggulan pada beban komputasi yang lebih rendah serta waktu pemroesesan yang lebih singkat, pendekatan ini memiliki permasalahan utama yakni inductive bias.

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*a**b* 

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* In American English, commas, semicolons, periods, question and exclamation marks are located within quotation marks only when a complete thought or name is cited, such as a title or full quotation. When quotation marks are used, instead of a bold or italic typeface, to highlight a word or phrase, punctuation should appear outside of the quotation marks. A parenthetical phrase or statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.)
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##### References

[1] Birkhoff G. *Hydrodynamics: A study in logic, fact and similitude: Revised edition*. Princeton University Press, 2015.

[2] Umgiesser G, Ferrarin C, Bajo M, et al. Hydrodynamic modelling in marginal and coastal seas — The case of the Adriatic Sea as a permanent laboratory for numerical approach. *Ocean Model (Oxf)* 2022; 179: 102123.

[3] Dudley JM, Genty G, Mussot A, et al. Rogue waves and analogies in optics and oceanography. *Nature Reviews Physics 2019 1:11* 2019; 1: 675–689.

[4] Huang J, Wang T, Liang J, et al. Biorobotic Waterfowl Flipper with Skeletal Skins in a Computational Framework: Kinematic Conformation and Hydrodynamic Analysis. *Advanced Intelligent Systems* 2023; 5: 2200380.

[5] Shihua JM, Liem RP, Li Y. An Improved Experimental Framework of Amphibious Marine Vehicle Hull Hydrodynamics. *IEEE Journal of Oceanic Engineering* 2024; 49: 80–91.

[6] Ahmadi SM, Ahmadi MT. Hydrodynamic considerations for improving the design/evaluation of over-topped bridge decks during extreme floods. *Structure and Infrastructure Engineering* 2024; 20: 1819–1833.

[7] Polycarpou AC. Introduction to the Finite Element Method in Electromagnetics. Epub ahead of print 2006. DOI: 10.1007/978-3-031-01689-9.

[8] Khanday MA. Numerical study of partial differential equations to estimate thermoregulation in human dermal regions for temperature dependent thermal conductivity. *Journal of the Egyptian Mathematical Society* 2014; 22: 152–155.

[9] Vacondio R, Altomare C, De Leffe M, et al. Grand challenges for Smoothed Particle Hydrodynamics numerical schemes. *Computational Particle Mechanics 2020 8:3* 2020; 8: 575–588.

[10] Panchigar D, Kar K, Shukla S, et al. Machine learning-based CFD simulations: a review, models, open threats, and future tactics. *Neural Comput Appl* 2022; 34: 21677–21700.

[11] Berzins M, Lofstead J, Chou J, et al. Parallel and scalable AI in HPC systems for CFD applications and beyond. *Frontiers in High Performance Computing* 2024; 2: 1444337.

[12] Choi S, Jung I, Kim H, et al. Physics-informed deep learning for data-driven solutions of computational fluid dynamics. *Korean Journal of Chemical Engineering* 2022; 39: 515–528.

[13] Kou J, Zhang W. Data-driven modeling for unsteady aerodynamics and aeroelasticity. *Progress in Aerospace Sciences* 2021; 125: 100725.

[14] Zhu Y, Dinh N. A Data-driven Approach for Turbulence Modeling. *17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 2017*; 2017-September, https://arxiv.org/abs/2005.00426v1 (2020, accessed 27 December 2024).

[15] Quang T Van, Doan DT, Phuong NL, et al. Data-driven prediction of indoor airflow distribution in naturally ventilated residential buildings using combined CFD simulation and machine learning (ML) approach. *J Build Phys* 2024; 47: 439–471.

[16] Nemati M, Jahangirian A. A Data-Driven Machine Learning Approach for Turbulent Flow Field Prediction Based on Direct Computational Fluid Dynamics Database. *Journal of Applied Fluid Mechanics* 2023; 17: 60–74.

[17] Chen WH, Chang CM, Mutuku JK, et al. Analysis of microparticle deposition in the human lung by taguchi method and response surface methodology. *Environ Res* 2021; 197: 110975.

[18] Li J, Wang T, Zhang L, et al. Multi-objective optimization of axial-flow-type gas-particle cyclone separator using response surface methodology and computational fluid dynamics. *Atmos Pollut Res* 2020; 11: 1487–1499.

[19] Phan L, Lin CX. CFD-based response surface methodology for rapid thermal simulation and optimal design of data centers. *Advances in Building Energy Research* 2020; 14: 471–493.

[20] Thakkar S, Vala H, Patel VK, et al. Performance improvement of the sanitary centrifugal pump through an integrated approach based on response surface methodology, multi-objective optimization and CFD. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 2021; 43: 1–15.

[21] Singh V. Application of response surface methodology and computational fluid dynamics for analyzing and optimizing the performance of finned solar air heater. *https://doi.org/101177/09544062241278187*. Epub ahead of print 27 September 2024. DOI: 10.1177/09544062241278187.

[22] Zhang G, Liu S. Reconstruction of Unsteady Wind Field Based on CFD and Reduced-Order Model. *Mathematics 2023, Vol 11, Page 2223* 2023; 11: 2223.

[23] Garbo A, Bekemeyer P. Unsteady physics-based reduced order modeling for large-scale compressible aerodynamic applications. *Comput Fluids* 2022; 239: 105385.

[24] Hajisharifi A, Romanò F, Girfoglio M, et al. A non-intrusive data-driven reduced order model for parametrized CFD-DEM numerical simulations. *J Comput Phys* 2023; 491: 112355.

[25] Chen X, Zhong W, Li T. Fast prediction of temperature and chemical species distributions in pulverized coal boiler using POD reduced-order modeling for CFD. *Energy* 2023; 276: 127663.

[26] Ranade R, Hill C, Pathak J. DiscretizationNet: A machine-learning based solver for Navier–Stokes equations using finite volume discretization. *Comput Methods Appl Mech Eng* 2021; 378: 113722.

[27] Sousa P, Rodrigues CV, Afonso A. Enhancing CFD solver with Machine Learning techniques. *Comput Methods Appl Mech Eng* 2024; 429: 117133.

[28] Rout S, Dwivedi V, Srinivasan B. Numerical Approximation in CFD Problems Using Physics Informed Machine Learning, https://arxiv.org/abs/2111.02987v1 (2021, accessed 27 December 2024).

[29] Grimberg S, Farhat C. Hyperreduction of cfd models of turbulent flows using a machine learning approach. *AIAA Scitech 2020 Forum* 2020; 1 PartF: 1–13.

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