

Recent Advances on Machine Learning for Computational Fluid Dynamics: A Survey

Haoxin Wang, Yadi Cao, Zijie Huang, Yuxuan Liu, Peiyan Hu, Xiao Luo, Zezheng Song, Wanjia Zhao, Jilin Liu, Jinan Sun[†], Shikun Zhang, Long Wei, Yue Wang, Tailin Wu, Zhi-Ming Ma, Yizhou Sun

Abstract—This paper explores the recent advancements in enhancing Computational Fluid Dynamics (CFD) tasks through Machine Learning (ML) techniques. We begin by introducing fundamental concepts, traditional methods, and benchmark datasets, then examine the various roles ML plays in improving CFD. The literature systematically reviews papers in recent five years and introduces a novel classification for forward modeling: Data-driven Surrogates, Physics-Informed Surrogates, and ML-assisted Numerical Solutions. Furthermore, we also review the latest ML methods in inverse design and control, offering a novel classification and providing an in-depth discussion. Then we highlight real-world applications of ML for CFD in critical scientific and engineering disciplines, including aerodynamics, combustion, atmosphere & ocean science, biology fluid, plasma, symbolic regression, and reduced order modeling. Besides, we identify key challenges and advocate for future research directions to address these challenges, such as multi-scale representation, physical knowledge encoding, scientific foundation model and automatic scientific discovery. This review serves as a guide for the rapidly expanding ML for CFD community, aiming to inspire insights for future advancements. We draw the conclusion that ML is poised to significantly transform CFD research by enhancing simulation accuracy, reducing computational time, and enabling more complex analyses of fluid dynamics. The paper resources can be viewed at <https://github.com/WildDynamics/Awesome-AI4CFD>.

Index Terms—Machine Learning, Computational Fluid Dynamics, AI for PDE, Physics Simulation, Inverse Problem.

1 INTRODUCTION

FLUID dynamics is a fundamental discipline that studies the motion and behavior of fluid flow. It serves as a foundation across a wide range of scientific and engineering fields, including aerodynamics [1], [2], [3], chemical engineering [4], [5], [6], biology [7], [8], [9], and environmental science [10], [11], [12], [13], [14], [15]. CFD employs mathematical models to simulate fluid dynamics through partial differential equations (PDEs) [16]. The primary goal of CFD is to obtain simulated results under various working conditions, thereby reducing the need for costly real-world experiments and accelerating engineering design and control processes.

Despite decades of advancement in research and engineering practice, CFD techniques continue to face significant challenges. These include high computational costs due to demanding restrictions on spatial or temporal resolutions, difficulties in capturing subscale dynamics such as in turbulence [17], and stability issues with numerical algorithms [16], among others. On the other hand, ML, famous for its ability to learn patterns and dynamics from observed data, has recently emerged as a trend that can reshape or enhance any general scientific subject [18]. The integration

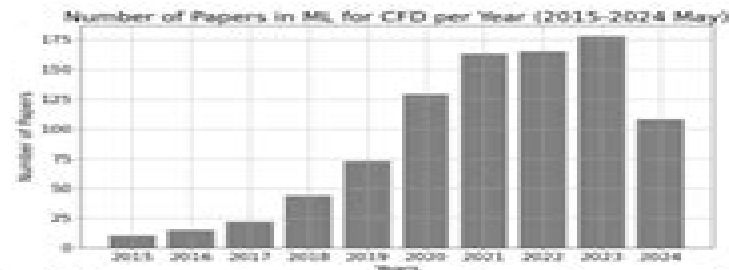


Fig. 1: The approximate annual number of papers on ML for CFD presented at top-tier ML publication and leading journals in fluid dynamics appeared in Table 1 and 2

of ML techniques with the extensive fluid dynamics data accumulated over recent decades offers a transformative approach to augment CFD practices (see Fig. 1). As the field of ML continues to expand rapidly, it becomes increasingly challenging for researchers to stay updated. In response, this review aims to shed light on the multifaceted roles ML plays in enhancing CFD.

Actually, there have already been some surveys on the application of ML methods in the CFD field. However, most of these surveys have the following two limitations: 1) **Only earlier attempts**. For instance, Wang *et al.* [19] and Huang *et al.* [20] both provide a detailed discussion on incorporating physics-based modeling into ML, emphasizing dynamic systems and hybrid approaches. Similarly, Vinuesa *et al.* [21] explores promising ML directions from the perspective of CFD domain, such as direct numerical simulations, a

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- P. Hu and Z. Ma are from Academy of Mathematics and Systems Science, Chinese Academy of Sciences.
- Z. Song is from University of Maryland, College Park.
- W. Zhao is from Stanford University.
- L. Wei and T. Wu work at Westlake University.
- Y. Wang works at Microsoft AHSIcenter.
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Recent Advances In Computational Fluid Dynamics

Rupak Biswas



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Recent Advances in Computational Fluid Dynamics C. C. Chao, 1989 *Recent Advances in Computational Fluid Dynamics*, 1973 **Recent Advances in Computational Fluid Dynamics** C.C. Chao, Steven A. Orszag, W. Shyy, 2013-03-07

From the preface Fluid dynamics is an excellent example of how recent advances in computational tools and techniques permit the rapid advance of basic and applied science The development of computational fluid dynamics CFD has opened new areas of research and has significantly supplemented information available from experimental measurements Scientific computing is directly responsible for such recent developments as the secondary instability theory of transition to turbulence dynamical systems analyses of routes to chaos ideas on the geometry of turbulence direct simulations of turbulence three dimensional full aircraft flow analyses and so on We believe that CFD has already achieved a status in the tool kit of fluid mechanicians equal to that of the classical scientific techniques of mathematical analysis and laboratory experiment

Recent Advances in Computational Mechanics and Simulations Sandip Kumar Saha, Mousumi Mukherjee, 2020-11-13 This volume presents selected papers from the 7th International Congress on Computational Mechanics and Simulation held at IIT Mandi India The papers discuss the development of mathematical models representing physical phenomena and applying modern computing methods and simulations to analyse them The studies cover recent advances in the fields of nano mechanics and biomechanics simulations of multiscale and multiphysics problems developments in solid mechanics and finite element method advancements in computational fluid dynamics and transport phenomena and applications of computational mechanics and techniques in emerging areas The volume will be of interest to researchers and academics from civil engineering mechanical engineering aerospace engineering materials engineering science physics mathematics and other disciplines *Recent Advances in Fluid Dynamics* Jyotirmay Banerjee, Rupesh D. Shah, Ramesh K. Agarwal, Sushanta

Mitra, 2022-09-24 This book presents select proceedings of the International Conference on Advances in Fluid Flow and Thermal Sciences ICAFFTS 2021 and summarizes the modern research practices in fluid dynamics and fluid power The content of the book involves advanced topics on turbulence droplet deposition oscillating flows wave breaking spray structure and its atomization and flow patterns in mini and micro channels Technological concerns relevant to erosion of steam turbine blade due to droplets influence of baffle cut and baffle pitch on flow regime bubble formation and propagation in pool boiling design optimization of flow regulating valves are included in the book In addition recent trends in small scale hydropower plant and flow stability issues in nanofluids solar water heating systems and closed loop pulsating heat pipes are discussed Special topics on airflow pattern in railway coach and vortex tube are also included This book will be a reliable reference for academicians researchers and professionals working in the areas of fluid dynamics and fluid power *Recent Advances In Computational Science And Engineering - Proceedings Of The International Conference On Scientific And Engineering Computation (Ic-sec) 2002* Justin Kwok, Heow-pueh Lee, Kurichi Kumar, 2002-12-02 IC SEC 2002 serves as a

forum for engineers and scientists who are involved in the use of high performance computers advanced numerical strategies computational methods and simulation in various scientific and engineering disciplines The conference creates a platform for presenting and discussing the latest trends and findings about the state of the art in their particular field s of interest IC SEC also provides a forum for the interdisciplinary blending of computational efforts in various diversified areas of science such as biology chemistry physics and materials science as well as all branches of engineering The proceedings cover a broad range of topics and an application area which involves modelling and simulation work using high performance computers

Some Recent Advances in Computational Aerodynamics for Helicopter Applications W. J. McCroskey,1985 Recent Advances in Computational Engineering Michael Schäfer,Marek Behr,Miriam Mehl,Barbara Wohlmuth,2018-08-21 This book comprises the proceedings of the 4th International Conference on Computational Engineering ICCE 2017 held in Darmstadt Germany on September 28 29 2017 The conference is intended to provide an interdisciplinary meeting place for researchers and practitioners working on computational methods in all disciplines of engineering applied mathematics and computer science The aims of the conference are to discuss the state of the art in this challenging field exchange experiences develop promising perspectives for future research and initiate further cooperation Computational Engineering is a modern and multidisciplinary science for computer based modeling simulation analysis and optimization of complex engineering applications and natural phenomena The book contains an overview of selected approaches from numerics and optimization of Partial Differential Equations as well as uncertainty quantification techniques typically in multiphysics environments

Where possible application cases from engineering are integrated The book will be of interest to researchers and practitioners of Computational Engineering Applied Mathematics Engineering Sciences and Computer Science *Special Issue: Recent Advances in Simulations of CFD-based* Pengfei Liu,Chemical Society of Canada,2006 **Parallel**

Computational Fluid Dynamics Rupak Biswas,2010 **Recent Advances in CFD for Wind and Tidal Offshore Turbines** Esteban Ferrer,Adeline Montlaur,2019-02-06 The book presents novel Computational Fluid Dynamics CFD techniques to compute offshore wind and tidal applications The papers in this volume are based on a mini symposium held at ECCOMAS 2018 Computational fluid dynamics CFD techniques are regarded as the main design tool to explore the new engineering challenges presented by offshore wind and tidal turbines for energy generation The difficulty and costs of undertaking experimental tests in offshore environments have increased the interest in CFD which is used to design appropriate turbines and blades understand fluid flow physical phenomena associated with offshore environments predict power production or characterise offshore environments amongst other topics **Recent Advances in Energy**

Technologies N. Lakshmi Narasimhan,Mahmoud Bourouis,Vasudevan Raghavan,2022-09-29 This book presents the select proceedings of the first International Conference on Energy and Materials Technologies ICEMT 2021 organized by the Department of Mechanical Engineering Sri Sivasubramaniya Nadar College of Engineering Kalavakkam India It covers the

recent technologies in two broad thematic areas energy and materials Various topics covered in this book include hybrid energy advanced energy systems energy management energy policy geothermal nuclear energy bio energy waste to energy power plants and automobiles The book will be useful for students researchers and professionals in the area of mechanical engineering especially various domains of energy

Recent Advances in Mechanical Engineering, Volume 1 Gujjala Raghavendra, B. B. V. L. Deepak, Manoj Gupta, 2024-04-01 This book presents select proceedings of International Conference on Mechanical Engineering Researches and Evolutionary Challenges ICMech REC 23 It covers the latest research in the areas of mechanical engineering and materials applications Various topics covered in this book are materials composite nano advanced design methodologies Industry 4.0 smart manufacturing thermodynamics mechatronics robotics soft computing and automation The contents of this book are useful to the researchers and professionals working in the different areas of mechanical engineering

Recent Advances in Mechatronics Tomas Brezina, Ryszard Jablonski, 2009-11-29 Mechatronics is a synergic discipline integrating precise mechanics electrotechnics electronics and IT technologies The main goal of mechatronical approach to design of complex products is to achieve new quality of their utility value at reasonable price Successful accomplishment of this task would not be possible without application of advanced software and hardware tools for simulation of design technologies and production control and also for simulation of behavior of these products in order to provide the highest possible level of spatial and functional integration of the final product This book brings a review of the current state of the art in mechatronics as presented at the 8th International Conference Mechatronics 2009 organized by the Brno Technical University Faculty of Mechanical Engineering Czech Republic The specific topics of the conference are Modelling and Simulation Metrology Diagnostics Sensorics Photonics Control Robotics MEMS Design Mechatronic Products Production Machines and Biomechanics The selected contributions provide an insight into the current development of these scientific disciplines present the new results of research and development and indicate the trends of development in the interdisciplinary field of mechatronic systems Therefore the book provides the latest and helpful information both for the R D specialists and for the designers working in mechatronics and related fields

IUTAM Symposium on Recent Advances in Moving Boundary Problems in Mechanics Stefanie Gutschmidt, James N. Hewett, Mathieu Sellier, 2019-03-28 Many problems in mechanics involve deformable domains with moving boundaries including fluid structure interaction multiphase flows flows over soft tissues and textiles or flows involving accretion erosion to name but a few The presence of a moving boundary presents considerable challenges when it comes to modelling and understanding the underlying system dynamics This proceedings volume collects contributions made at the IUTAM Symposium on Recent Advances in Moving Boundary Problems in Mechanics held in Christchurch New Zealand in February 2018

Recent Advances in Spray Combustion Kenneth K. Kuo, 1996

Recent Advancements in Product Design and Manufacturing Systems B B V L Deepak, M.V.A. Raju Bahubalendruni, D.R.K. Parhi, B. B. Biswal, 2024-11-16 This book presents select proceedings of the 5th Innovative

Product Design and Intelligent Manufacturing System IPDIMS 2023 conference It covers concepts and recent methods that are implemented in intelligent manufacturing systems along with the product innovation technologies The broad topics covered include Industry 4.0 Industry 5.0 smart manufacturing advanced robotics product innovation and CAD CAM CIM The contents of this book are useful for academics as well as professionals working in the areas of mechatronics mechanical manufacturing production and industrial engineering

Error Estimation and Adaptive Discretization Methods in Computational Fluid Dynamics Timothy J. Barth, Herman Deconinck, 2013-04-17 As computational fluid dynamics CFD is applied to ever more demanding fluid flow problems the ability to compute numerical fluid flow solutions to a user specified tolerance as well as the ability to quantify the accuracy of an existing numerical solution are seen as essential ingredients in robust numerical simulation Although the task of accurate error estimation for the nonlinear equations of CFD seems a daunting problem considerable effort has centered on this challenge in recent years with notable progress being made by the use of advanced error estimation techniques and adaptive discretization methods To address this important topic a special course was jointly organized by the NATO Research and Technology Office RTO the von Karman Institute for Fluid Dynamics and the NASA Ames Research Center The NATO RTO sponsored course entitled Error Estimation and Solution Adaptive Discretization in CFD was held September 10-14 2002 at the NASA Ames Research Center and October 15-19 2002 at the von Karman Institute in Belgium During the special course a series of comprehensive lectures by leading experts discussed recent advances and technical progress in the area of numerical error estimation and adaptive discretization methods with specific emphasis on computational fluid dynamics The lecture notes provided in this volume are derived from the special course material The volume consists of 6 articles prepared by the special course lecturers

Parallel Computational Fluid Dynamics '98 Chiao-ling Lin, P. Fox, A. Ecer, N. Satofuka, Jacques Periaux, 1999-05-26 This book contains the papers presented at the Parallel Computational Fluid Dynamics 1998 Conference The book is focused on new developments and applications of parallel technology Key topics are introduced through contributed papers and invited lectures These include typical algorithmic developments such as distributed computing domain decomposition and parallel algorithm Some of the papers address the evaluations of software and machine performance and software tool environments The application of parallel computers to complex fluid dynamics problems are also conveyed through sessions such as DNS LES combustion and reacting flows industrial applications water resources and environmental flows The editors believe this book will provide many researchers much beyond those contributing to this volume with fresh information and reference

Recent Advances in Infrastructure Development and Management - Volume 2 Y. K. Guruprasad, G. R. Dodagoudar, K. S. Nanjunda Rao, P. C. Pandey, H. B. Nagaraj, 2025-08-11 This book presents select proceedings of Modern Trends in Civil Engineering Infrastructure Development Management MTCEIDM 2023 It sheds light on the current research on the applications of innovative tools and technologies in solving real life civil engineering problems The book presents the application of such new technologies in

various domains including but not limited to structural health monitoring infrastructure and retrofitting futuristic and sustainable materials analysis and design of mega structures foundation design and safety assessment of structures and hydraulic and transportation structures This book would be a valuable resource for researchers and professionals dealing with innovative technologies in the field of infrastructure development and infrastructure management

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