

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

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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

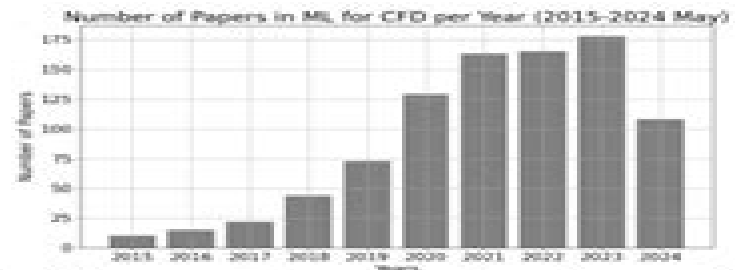


Fig. 1: The approximate annual number of papers on ML for CFD presented at top-tier ML publication and leading journals in fluid dynamics appeared in Table 1 and 2

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.
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 • Y. Wang works at Microsoft AHSIcenter.
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Recent Advances In Computational Fluid Dynamics

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Recent Advances in Computational Fluid Dynamics C. C. Chao, 1989 **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 Fluid Dynamics*, 1973

Recent Advances in Computational Mechanics and Simulations Sandip Kumar Saha, Mousumi Mukherjee, 2020-11-23 This book 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 apply modern computing methods to analyze a broad range of applications including civil offshore aerospace automotive naval and nuclear structures Special emphasis is given on simulation of structural response under extreme loading such as earthquake blast etc The book is of interest to researchers and academics from civil engineering mechanical engineering aerospace engineering materials engineering science physics mathematics and other disciplines *Parallel Computational Fluid Dynamics* Rupak Biswas, 2010 *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 fields 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

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

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CFD-based Pengfei Liu, Chemical Society of Canada, 2006 **Some Recent Advances in Computational Aerodynamics**

for Helicopter Applications W. J. McCroskey, 1985 **Recent Advances in Computational Mechanics and**

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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 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 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 Computational and Experimental Mechanics, Vol—I D. Maity, P. K. Patra, M. S. Afzal, R. Ghoshal, C. S. Mistry, P. Jana, D. K. Maiti, 2022-01-01. This book Vol I presents select proceedings of the first Online International Conference on Recent Advances in Computational and Experimental Mechanics ICRACEM 2020 and focuses on theoretical, computational and experimental aspects of solid and fluid mechanics. Various topics covered are: computational modelling of extreme events, mechanical modelling of robots, mechanics and design of cellular materials, mechanics of soft materials, mechanics of thin film and multi layer structures, meshfree and particle based formulations in continuum mechanics, multi scale computations in solid mechanics and materials, multiscale mechanics of brittle and ductile materials, topology and shape optimization techniques, acoustics including aero acoustics and wave propagation, aerodynamics, dynamics and control in micro nano engineering, dynamic instability and buckling, flow induced noise and vibration, inverse problems in mechanics and system identification, measurement and analysis techniques in nonlinear dynamic systems, multibody dynamical systems and applications, nonlinear dynamics and control, stochastic mechanics, structural dynamics and earthquake engineering, structural health monitoring and damage assessment, turbomachinery noise, vibrations of continuous systems, characterization of advanced materials, damage identification and non destructive evaluation, experimental fire mechanics and damage, experimental fluid mechanics, experimental solid mechanics.

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AD2012 conference cover the application of AD to many areas in science and engineering as well as aspects of AD theory and its implementation in tools For all papers the referees selected from the program committee and the greater community as well as the editors have emphasized accessibility of the presented ideas also to non AD experts In the AD tools arena new implementations are introduced covering for example Java and graphical modeling environments or join the set of existing tools for Fortran New developments in AD algorithms target the efficiency of matrix operation derivatives detection and exploitation of sparsity partial separability the treatment of nonsmooth functions and other high level mathematical aspects of the numerical computations to be differentiated Applications stem from the Earth sciences nuclear engineering fluid dynamics and chemistry to name just a few In many cases the applications in a given area of science or engineering share characteristics that require specific approaches to enable AD capabilities or provide an opportunity for efficiency gains in the derivative computation The description of these characteristics and of the techniques for successfully using AD should make the proceedings a valuable source of information for users of AD tools

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 mechatronic 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

Recent Numerical Advances in Fluid Mechanics Omer San, 2020-07-03 In recent decades the field of computational fluid dynamics has made significant advances in enabling advanced computing architectures to understand many phenomena in biological geophysical and engineering fluid flows Almost all research areas in fluids use numerical methods at various complexities from molecular to continuum descriptions from laminar to turbulent regimes from low speed to hypersonic from stencil based computations to meshless approaches from local basis functions to global expansions as well as from first order approximation to high order with spectral accuracy Many successful efforts have been put forth in dynamic adaptation strategies e g adaptive mesh refinement and multiresolution representation approaches

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