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

\*Note: Sub-titles are not captured in Xplore and should not be used

line 1: 1st Given Name Surname   
line 2: *dept. name of organization   
(of Affiliation)*  
line 3: *name of organization   
(of Affiliation)*line 4: City, Country  
line 5: email address or ORCID

line 1: 4th Given Name Surname  
line 2: *dept. name of organization*  
*(of Affiliation)*  
line 3: *name of organization   
(of Affiliation)*line 4: City, Country  
line 5: email address or ORCIDline 1: 2nd Given Name Surname  
line 2: *dept. name of organization   
(of Affiliation)*  
line 3: *name of organization   
(of Affiliation)*line 4: City, Country  
line 5: email address or ORCID

line 1: 5th Given Name Surname  
line 2: *dept. name of organization   
(of Affiliation)*  
line 3: *name of organization   
(of Affiliation)*line 4: City, Country  
line 5: email address or ORCIDline 1: 3rd Given Name Surname  
line 2: *dept. name of organization   
(of Affiliation)*  
line 3: *name of organization   
(of Affiliation)*line 4: City, Country  
line 5: email address or ORCID

line 1: 6th Given Name Surname  
line 2: *dept. name of organization   
(of Affiliation)*  
line 3: *name of organization   
(of Affiliation)*line 4: City, Country  
line 5: email address or ORCID

*Abstract*—This electronic document is a “live” template and already defines the components of your paper [title, text, heads, etc.] in its style sheet. *\*CRITICAL: Do Not Use Symbols, Special Characters, Footnotes, or Math in Paper Title or Abstract*. (*Abstract*)

Keywords—component, formatting, style, styling, insert (key words)

# 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.

A graph of red squares

Description automatically generated

1. Example of a figure caption. (*figure caption*)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 1. Table Type Styles  |  |  |  |  | | --- | --- | --- | --- | | copy | More table ` |  |  | |

# Governing Equation Overview

## Ocean Wave

First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the Microsoft Word, Letter file.

|  |  |
| --- | --- |
|  |  |
|  |  |

## Maintaining the Integrity of the Specifications

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

# Prepare Your Paper Before Styling

Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections A-D below for more information on proofreading, spelling and grammar.

Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

## Abbreviations and Acronyms

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

## Units

* Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as “3.5-inch disk drive”.
* Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity that you use in an equation.
* Do not mix complete spellings and abbreviations of units: “Wb/m2” or “webers per square meter”, not “webers/m2”. Spell out units when they appear in text: “. . . a few henries”, not “. . . a few H”.

Identify applicable funding agency here. If none, delete this text box.

* Use a zero before decimal points: “0.25”, not “.25”. Use “cm3”, not “cc”. (*bullet list*)

## Equations

The equations are an exception to the prescribed specifications of this template. You will need to determine whether or not your equation should be typed using either the Times New Roman or the Symbol font (please no other font). To create multileveled equations, it may be necessary to treat the equation as a graphic and insert it into the text after your paper is styled.

Number equations consecutively. Equation numbers, within parentheses, are to position flush right, as in (1), using a right tab stop. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Italicize Roman symbols for quantities and variables, but not Greek symbols. Use a long dash rather than a hyphen for a minus sign. Punctuate equations with commas or periods when they are part of a sentence, as in:

*a**b* 

Note that the equation is centered using a center tab stop. Be sure that the symbols in your equation have been defined before or immediately following the equation. Use “(1)”, not “Eq. (1)” or “equation (1)”, except at the beginning of a sentence: “Equation (1) is . . .”

## Some Common Mistakes

* The word “data” is plural, not singular.
* The subscript for the permeability of vacuum **0, and other common scientific constants, is zero with subscript formatting, not a lowercase letter “o”.
* 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.)
* A graph within a graph is an “inset”, not an “insert”. The word alternatively is preferred to the word “alternately” (unless you really mean something that alternates).
* Do not use the word “essentially” to mean “approximately” or “effectively”.
* In your paper title, if the words “that uses” can accurately replace the word “using”, capitalize the “u”; if not, keep using lower-cased.
* Be aware of the different meanings of the homophones “affect” and “effect”, “complement” and “compliment”, “discreet” and “discrete”, “principal” and “principle”.
* Do not confuse “imply” and “infer”.
* The prefix “non” is not a word; it should be joined to the word it modifies, usually without a hyphen.
* There is no period after the “et” in the Latin abbreviation “et al.”.
* The abbreviation “i.e.” means “that is”, and the abbreviation “e.g.” means “for example”.

An excellent style manual for science writers is [7].

# Using the Template

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

## Authors and Affiliations

**The template is designed for, but not limited to, six authors.** A minimum of one author is required for all conference articles. Author names should be listed starting from left to right and then moving down to the next line. This is the author sequence that will be used in future citations and by indexing services. Names should not be listed in columns nor group by affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization).

### For papers with more than six authors: Add author names horizontally, moving to a third row if needed for more than 8 authors.

### For papers with less than six authors: To change the default, adjust the template as follows.

#### Selection: Highlight all author and affiliation lines.

#### Change number of columns: Select the Columns icon from the MS Word Standard toolbar and then select the correct number of columns from the selection palette.

#### Deletion: Delete the author and affiliation lines for the extra authors.

## Identify the Headings

Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads.

Component heads identify the different components of your paper and are not topically subordinate to each other. Examples include Acknowledgments and References and, for these, the correct style to use is “Heading 5”. Use “figure caption” for your Figure captions, and “table head” for your table title. Run-in heads, such as “Abstract”, will require you to apply a style (in this case, italic) in addition to the style provided by the drop down menu to differentiate the head from the text.

Text heads organize the topics on a relational, hierarchical basis. For example, the paper title is the primary text head because all subsequent material relates and elaborates on this one topic. If there are two or more sub-topics, the next level head (uppercase Roman numerals) should be used and, conversely, if there are not at least two sub-topics, then no subheads should be introduced. Styles named “Heading 1”, “Heading 2”, “Heading 3”, and “Heading 4” are prescribed.

## Figures and Tables

#### Positioning Figures and Tables: Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation “Fig. 1”, even at the beginning of a sentence.

1. Table Type Styles

| Table Head | Table Column Head | | |
| --- | --- | --- | --- |
| Table column subhead | Subhead | Subhead |
| copy | More table copya |  |  |

1. Sample of a Table footnote. (*Table footnote*)
2. Example of a figure caption. (*figure caption*)

Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity “Magnetization”, or “Magnetization, M”, not just “M”. If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write “Magnetization (A/m)” or “Magnetization {A[m(1)]}”, not just “A/m”. Do not label axes with a ratio of quantities and units. For example, write “Temperature (K)”, not “Temperature/K”.

##### Acknowledgment *(Heading 5)*

The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression “one of us (R. B. G.) thanks ...”. Instead, try “R. B. G. thanks...”. Put sponsor acknowledgments in the unnumbered footnote on the first page.

##### 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.

**IEEE conference templates contain guidance text for composing and formatting conference papers. Please ensure that all template text is removed from your conference paper prior to submission to the conference. Failure to remove template text from your paper may result in your paper not being published.**