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Report Term: 0-Other
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STEM Degrees:

STEM Participants:

Major Goals: Over the past two decades, the fluid dynamics community has enjoyed the advancement in computational, experimental, and theoretical techniques to analyze a variety of fluid flows. Developments in computational and experimental hardware, numerical algorithms, and unsteady measurement techniques have enabled not only detailed analysis of flow physics but also initiated cross-talks amongst the various disciplines of fluid mechanics. With these powerful toolsets now available, the fluid dynamics community has started to examine complex flows with high levels of unsteadiness, nonlinearity, and multi-scale dynamics. However, there still exist limitations on how modern analysis techniques can be applied to specific fluid dynamics problems. Theoretical and computational approaches are often limited to relatively simple flows at low Reynolds numbers, while practical applications require extension to more complex unsteady and turbulent flows. Extending the current state of the art in flow analysis to higher Reynolds number flows requires tackling high-dimensional physics and the associated big-data from numerical simulations or experimental measurements. Some of the recent innovations in data science may hold the key to address these issues. The aim of this workshop is to gather fluid dynamics and data science experts from their respective areas and discuss their ongoing progress and challenges in emerging analysis techniques, including data science, computational & theoretical fluid dynamics, and advanced experimental diagnostic methods, that can be shared with others to facilitate breakthroughs as a community. This event will stimulate discussions and collaborations between members of the research communities to identify key areas that can make the largest impact and to offer a vehicle to further strengthen research collaborations across the Pacific. Following the success of the first “US-Japan Workshop on Bridging Data Science and Fluid Mechanics,” we are holding the second workshop now entitled the “US-Japan Workshop on Data-Driven Fluid Dynamics.”

Accomplishments: The second US-Japan Workshop on Data-Driven Fluid Dynamics took place in Kobe, Japan, from September 5 to 7, 2022. This workshop has originally scheduled to be held in March 2020 but has been postponed due to COVID-19 restrictions. The workshop had two and a half days of technical presentations, a visit to RIKEN's Center for Computational Science, and a banquet. The workshop was attended by 42 US and Japanese experts in the areas of fluid dynamics and data science from academia, government, and industry. Of the attendees, 30 were from Japan, and 12 were from the US with both fields of experimental and computational fluid dynamics well represented. The number of US attendees was decreased from the original plan due to the complex process of obtaining Japanese entry visa requirements imposed by strict COVID-19-related restrictions. The workshop enjoyed 2 keynote presentations and 22 regular presentations, along with two discussion sessions. This workshop was made possible by generous support from AOARD, ARO, Ebara Corporation, Hitachi, Honda R&D, Intelligent Light, MathWorks, and Morgenrot.

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Results Dissemination: Nothing to Report

Honors and Awards: 2022 K. Taira, DoD Vannevar Bush Faculty Fellowship

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PARTICIPANTS:

Participant Type: PD/PI
Participant: Kunihiko Taira
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Partners

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I certify that the information in the report is complete and accurate:
Signature: Kunihiko Taira
Signature Date: 1/31/23 2:07PM

2nd US-Japan Workshop on Data-Driven Fluid Dynamics

Final Report

September 05-07, 2022
Kobe Meriken Park Oriental Hotel, Kobe, Japan

Compiled by Kunihiko Taira
Mechanical and Aerospace Engineering, UCLA
on September 18, 2022

Abstract:

The second US-Japan Workshop on Data-Driven Fluid Dynamics took place in Kobe, Japan, from September 5 to 7, 2022. This workshop has originally scheduled to be held in March 2020 but has been postponed due to COVID-19 restrictions. The workshop had two and a half days of technical presentations, a visit to RIKEN's Center for Computational Science, and a banquet. The workshop was attended by 42 US and Japanese experts in the areas of fluid dynamics and data science from academia, government, and industry. Of the attendees, 30 were from Japan, and 12 were from the US with both fields of experimental and computational fluid dynamics well represented. The number of US attendees was decreased from the original plan due to the complex process of obtaining Japanese entry visa requirements imposed by strict COVID-19-related restrictions. The workshop enjoyed 2 keynote presentations and 22 regular presentations, along with two discussion sessions. This workshop was made possible by generous support from AOARD, ARO, Ebara Corporation, Hitachi, Honda R&D, Intelligent Light, MathWorks, and Morgenrot.

Workshop Report:

The second US-Japan Workshop on Data-Driven Fluid Dynamics took place in Kobe, Japan, from September 5 to 7, 2022. This workshop has originally scheduled to be held in March 2020 but has been postponed due to COVID-19 restrictions. The workshop had two and a half days of technical presentations, a visit to RIKEN's Center for Computational Science, and a banquet. The workshop was attended by 42 US and Japanese experts in the areas of fluid dynamics and data science from academia, government, and industry. Of the attendees, 30 were from Japan, and 12 were from the US with both fields of experimental and computational fluid dynamics well represented. The number of US attendees was decreased from the original plan due to the complex process of obtaining Japanese entry visa requirements imposed by strict COVID-19-related restrictions. The workshop enjoyed 2 keynote presentations and 22 regular presentations, along with two discussion sessions. This workshop was made possible by generous support from AOARD, ARO, Ebara Corporation, Hitachi, Honda R&D, Intelligent Light, MathWorks, and Morgenrot.

On day 1, the workshop started with the first keynote presentation by Prof. Petros Koumoutsakos from Harvard University. He presented an overview of his group's work on applying machine learning for a range of fluid dynamic applications and his efforts to extend beyond fluid mechanics with an analogy to alloy, mixing data-driven concepts into dynamical systems. The first day also had three sessions of talks focusing on turbulent flow modeling and estimation, unsteady flows, flow control, and data science education. Some highlights from these sessions include data-driven sensor placement algorithms with PIV measurements (Nonomura); identification of manifold that describes the low-dimensional dynamics of turbulence (Graham); modeling the influence of turbulence (Iliescu and Yeh); force decomposition method (Mittal); machine learning techniques (Fukagata and Fukami); unsteady aerodynamics (Jones and Taira), and industrial applications and education of data-driven methods (Inoue, Doke, Nucera, and Tatsukawa). The first day ended with a banquet at the hotel featuring local cuisines and an opportunity for the attendees to interact in a relaxed and friendly setting.

Day 2 started with the second keynote presentation by Prof. Takemasa Miyoshi from Riken. He spoke about his experience in developing data assimilation methods for weather forecasting in Japan, leveraging Fugaku's supercomputing capability. The second day also had one session comprised of talks on data-science applications in industry (An), high-Re flows (Yakeno), and commercial code development (Legensky). These topics stimulated interesting discussions on the utility of data-driven techniques in industrial applications. The majority of the attendees visited RIKEN's Center for Computational Science to tour the facility and to learn about supercomputing in Kobe. A special tour was provided highlighting the usage of supercomputing to advance Japan's national efforts on scientific discovery and advancing next-generation manufacturing.

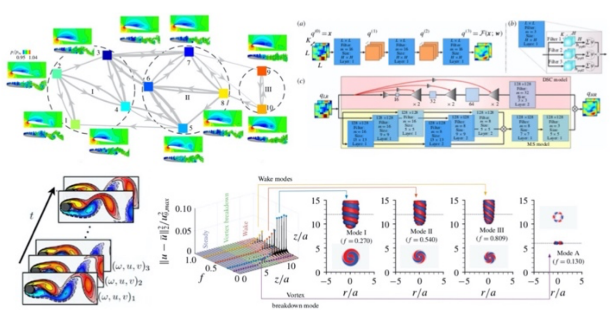
Day 3 had two sessions in the morning with talks focusing on machine learning-based modeling of turbulence, multi-phase flows, and reactive flows. Several studies offered novel approaches to examine the complex interactions (Goto) in high-Reynolds numbers and their closure problems (Kawai). There were also presentations on complex turbulent flow analysis, including the machine learning of multiphase flows (Okabayashi), optimal time-dependent mode analysis of reactive flows (Babaee), and complex systems investigation of thermo-acoustic instabilities (Gotoda). There was also the data-driven analysis for aircraft design (Abe). At the end of the workshop, a discussion session has held where some of the refreshing presentations were highlighted.

Compared to the first workshop held in 2018, there was a significant increase in studies that leveraged nonlinear machine learning techniques to tackle complex nonlinear dynamics present in fluid flows. Moreover, the implementations of data-driven/machine learning techniques appeared to be more prevalent in both computational and experimental fluid dynamics for the analysis, modeling, control, and design of various fluid-based systems. A large number of attendees expressed interest in a potential third workshop. It is hoped that this workshop stimulates creative ideas in data-driven fluid dynamics and new collaborations between the US and Japan.

Appendix: Program Booklet with Abstracts

Updated: Sep 03, 2022 [final]

2nd US-Japan Workshop on Data-Driven Fluid Dynamics



September 05-07, 2022
Kobe Meriken Park Oriental Hotel, Kobe, Japan

Sponsored by

Objectives:

Over the past two decades, the fluid dynamics community has enjoyed the advancement in computational, experimental, and theoretical techniques to analyze a variety of fluid flows. Developments in computational and experimental hardware, numerical algorithms, and unsteady measurement techniques have enabled not only detailed analysis of flow physics but also initiated cross-talks amongst the various disciplines of fluid mechanics. With these powerful toolsets now available, the fluid dynamics community has started to examine complex flows with high levels of unsteadiness, nonlinearity, and multi-scale dynamics. However, there still exist limitations on how modern analysis techniques can be applied to specific fluid dynamics problems. Theoretical and computational approaches are often limited to relatively simple flows at low Reynolds numbers, while practical applications require extension to more complex unsteady and turbulent flows. Extending the current state of the art in flow analysis to higher Reynolds number flows requires tackling high-dimensional physics and the associated big-data from numerical simulations or experimental measurements. Some of the recent innovations in data science may hold the key to address these issues. The aim of this workshop is to gather fluid dynamics and data science experts from their respective areas and discuss their ongoing progress and challenges in emerging analysis techniques, including data science, computational & theoretical fluid dynamics, and advanced experimental diagnostic methods, that can be shared with others to facilitate breakthroughs as a community. This event will stimulate discussions and collaborations between members of the research communities to identify key areas that can make the largest impact and to offer a vehicle to further strengthen research collaborations across the Pacific. Following the success of the first "US-Japan Workshop on Bridging Data Science and Fluid Mechanics," we are holding the second workshop now entitled the "US-Japan Workshop on Data-Driven Fluid Dynamics."

Target Areas:

Data-inspired techniques for fluid dynamics, including but not limited to data-driven analysis, modeling, estimation, and control of fluid flows.

Sponsors:

We thank the generous support from

Army Research Office
Asian Office of Aerospace Research and Development
Ebara Corporation
Hitachi Ltd.
Honda R&D Co., Ltd.
Intelligent Light
MathWorks
Morgenrot

Organizers

Steve Brunton (University of Washington)
Kozo Fujii (Tokyo University of Science)
Koji Fukagata (Keio University)
Maziar Hemati (University of Minnesota)
Masamichi Nakamura (Morgenrot)
Taku Nonomura (Tohoku University)
Kunihiko Taira (UCLA)

Attendees

Yoshiaki Abe (Tohoku University)
Kei Ambo (Honda R&D)
Dave Amels (Intelligent Light)
Byungjin An (Ebara)
Hessam Babaee (University of Pittsburgh)
Ryan Carr (AOARD)
Jiro Doke (Mathworks)
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Kai Fukami (UCLA)
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Yoshinobu Kawahara (Kyushu Univ/RIKEN)
Soshi Kawai (Tohoku University)
Yoimi Kojima (JAXA)
Petros Koumoutsakos (Harvard University) - **keynote speaker**
Steve Legenski (Intelligent Light)
Rajat Mittal (Johns Hopkins University)
Takemasa Miyoshi (RIKEN) - **keynote speaker**
Takayuki Nagata (Tohoku University)
Kumi Nakai (AIST)
Masamichi Nakamura (Morgenrot)
Yuki Nakamura (Honda R&D)
Akira Namatame (AOARD)
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Kunihiko Taira (UCLA)
Tomoaki Tatsukawa (Tokyo University of Science)
Atsushi Toyoda (Intelligent Light)
Aiko Yakeno (Tohoku University)
Chi-An Yeh (North Carolina State University)

SCHEDULE

DAY 1 (September 5)

REGISTRATION

8:00-8:45 **REGISTRATION AND COFFEE**

OPENING REMARKS AND LOGISTICS

8:45-9:00 **Kunihiko Taira (UCLA)**

KEYNOTE TALK (Chair: Kunihiko Taira)

9:00-10:00 **Petros Koumoutsakos (Harvard University)**
Alloys of AI and Computational Science for Modeling Prediction and Control in Fluid Mechanics

10:00-10:20 **COFFEE BREAK**

SESSION I (Chair: Kunihiko Taira)

10:20-10:45 **Taku Nonomura (Tohoku University)**
Advanced Fluid Measurement based on Active Use of Modal Decomposition

10:45-11:10 **Michael David Graham (University of Wisconsin-Madison)**
Data-Driven Manifold Dynamics for Modeling and Control

11:10-11:35 **Fortunato Nucera (Honda R&D)**
GAN-Based Automobile Flow Field Prediction from Simple Geometric Data

11:35-12:00 **Chi-An Yeh (North Carolina State University)**
Data-Enhanced Resolvent Analysis of Turbulent Flows

12:00-1:20 **LUNCH**

SESSION II (Chair: Koji Fukagata)

1:20-1:45 **Jiro Doke (MathWorks)**
MATLAB Ecosystem: Teaching Tool in the Field of Data Science

1:45-2:10 **Michio Inoue (MathWorks)**
MATLAB Ecosystem: Data Science with Open Source and Beyond

2:10-2:35 **Rajat Mittal (Johns Hopkins University)**
The Force Partitioning Method: A Data-Enabled Method for Dissecting Aerodynamic Forces in Vortex Dominated Flows

2:35-3:00 **Traian Iliescu (Virginia Tech)**
ROM Closures and Stabilizations for Turbulent Flows

3:00-3:20 COFFEE BREAK

SESSION III (Chair: Rajat Mittal)

3:20-3:45 **Koji Fukagata (Keio University)**
Reduced Order Modeling and Estimation of Flow Fields Using Convolutional Neural Networks – Towards Machine Learning Assisted Flow Control

3:45-4:10 **Anya Jones (University of Maryland)**
Towards New Methods of Lift Regularization in Discrete Gusts

4:10-4:35 **Kunihiko Taira (UCLA)**
Toward Extreme Aerodynamics with Data-Driven Approaches

4:35-5:00 **Kai Fukami (UCLA)**
Reconstructing and Modeling Unsteady Flows with Physics-Inspired Machine Learning

5:00-5:25 **Tomoaki Tatsukawa, Kozo Fujii (Tokyo University of Science)**
Extraction of Speed-Control Strategy in En-Route Air Traffic Flows using Multi-Objective Optimization and Machine Learning

7:00-9:00 BANQUET

DAY 2 (September 6)

KEYNOTE TALK (Chair: Kozo Fujii)

9:00-10:00 **Takemasa Miyoshi (RIKEN)**
Big Data Assimilation Revolutionizing Numerical Weather Prediction Using Fugaku

10:00-10:20 COFFEE BREAK

SESSION IV (Chair: Kozo Fujii)

10:20-10:45 **Byungjin An (Ebara Corporation)**
Data Science Application in Ebara

10:45-11:10 **Aiko Yakeno (Tohoku University)**
Challenges for Delaying Transition to Reduce Airplane Drag

11:10-11:35 **Steve M. Legensky, David A. Amels, Earl P. N. Duque & Atsushi Toyoda (Intelligent Light)**
Augmenting DMD and Frequency Analysis with Visualization for Engineering Applications

DISCUSSION

11:35-12:00 **Moderator: Koji Fukagata**

12:00-1:30 LUNCH

TOUR OF RIKEN CENTER FOR COMPUTATIONAL SCIENCE

Depart the hotel at 1:30. Detailed schedule will be shared at the workshop. Bus available from hotel to Riken. Attendees will be split up in two groups (tours will end around 3:00 or 3:30 depending on your assigned group). Please use public transportation for the return trip. Attendees are free to explore the city of Kobe after this tour.

https://www.r-ccs.riken.jp/en/

DAY 3 (September 7)

SESSION V (Chair: Michael Graham)

9:00-9:25 **Susumu Goto (Osaka University)**
Application of Reservoir Computing to Turbulence

9:25-9:50 **Kie Okabayashi (Osaka University)**
Preliminary Study on Learning and Test Modes of Data-Driven Cavitation Model

9:50-10:15 **Soshi Kawai (Tohoku University)**
Unsupervised Machine-Learning for Super-Resolution and SGS Modeling of Very Coarse-Grid LES

10:15-10:35 COFFEE BREAK

SESSION VI (Chair: Taku Nonomura)

10:35-11:00 **Hiroshi Gotoda (Tokyo University of Science)**
Complex-Systems Analysis of Thermoacoustic Combustion Instability in a Swirl-Stabilized Combustor

11:00-11:25 **Hessam Babaee (University of Pittsburgh)**
Reduced-Order Modeling Using Time-Dependent Bases with Applications to Turbulent Combustion

11:25-11:50 **Yoshiaki Abe and Shigeru Obayashi (Tohoku University)**
Digital Transformation of Aircraft Design with Carbon Fiber Reinforced Plastics

DISCUSSION

11:50-12:10 **Moderator: Kunihiko Taira**

CLOSING REMARKS

12:10-12:20 **Kozo Fujii (Tokyo University of Science)**

12:20-1:30 LUNCH & AJOURN

Abstracts

KEYNOTE TALKS (50 minutes + 10 minutes Q&A)

Petros Koumoutsakos (Harvard University)

Alloys of AI and Computational Science for Modeling Prediction and Control in Fluid Mechanics

Over the last thirty years we have experienced more than a billion-fold increase in hardware capabilities and a dizzying pace of acquiring and transmitting massive amounts of data. Artificial Intelligence (AI) has been the beneficiaries of these advances and today it is increasingly embedded in technologies that touch every aspect of humanity. In this talk I would offer a perspective on forming alloys of AI and simulations for the prediction and control of complex flow systems. I will present novel algorithms for learning the Effective Dynamics (LED) of complex flows and a fusion of multi-agent reinforcement learning and scientific computing (SciMARL) for modeling and control of complex flow-structure interactions. I will juxtapose successes and failures and argue that the proper fusion of fluid mechanics knowledge and AI expertise is essential to advance scientific frontiers.

Takemasa Miyoshi (RIKEN)

Big Data Assimilation Revolutionizing Numerical Weather Prediction Using Fugaku

At RIKEN, we have been exploring a fusion of big data and big computation in numerical weather prediction (NWP), and now with AI and machine learning (ML). Our group in RIKEN has been pushing the limits of NWP through two orders of magnitude bigger computations using the previous Japan's flagship "K computer". The efforts include 100-m mesh, 30-second update "Big Data Assimilation" (BDA) fully exploiting the big data from a novel Phased Array Weather Radar. With the new Fugaku, we achieved a real-time BDA application to predict sudden downpours up to 30 minutes in advance during Tokyo Olympics and Paralympics. Moreover, Fugaku is designed to be efficient for both double-precision big simulations and reduced-precision ML applications, aiming to play a pivotal role in creating super-smart "Society 5.0." We have been exploring ideas for improving the predicting capabilities by fusing BDA and AI. The data produced by NWP models become bigger and moving the data to other computers for ML or even simply saving them may not be feasible. A next-generation computer like Fugaku may bring a breakthrough toward creating a new methodology of fusing data-driven (inductive) and process-driven (deductive) approaches in meteorology. This presentation will introduce the most recent results from BDA experiments, followed by perspectives toward DA-AI fusion and expanding new applications beyond meteorology.

REGULAR TALKS (20 minutes + 5 minutes Q&A)

Yoshiaki Abe and Shigeru Obayashi (Tohoku University)

Digital Transformation of Aircraft Design with Carbon Fiber Reinforced Plastics

Digital design of aircraft has been one of the most challenging topics in engineering fields, which requires highly multidisciplinary simulation tools and has yet to be fully realized in industries. This study has developed a multiscale design framework of aircraft wings with carbon fiber reinforced plastics (CFRPs), wherein a multiobjective design exploration of wing geometries were performed using a genetic algorithm. The underpinning tool starts with evaluating mechanical properties of a unidirectional laminate via a microscale analysis of carbon fiber and matrix resin, which are subsequently applied to macroscale analyses of a steady-state fluid-structure-coupled simulation with structural sizing. The framework is able to estimate trade-off solutions of CFRP wing structures based on only the material properties of carbon fiber and matrix resin. The optimization was demonstrated for the aircraft-grade fibers of T700S, T800S, and T1100G, wherein the trade-off solutions achieve the higher performance, i.e., weight and drag reduction, by increasing the stiffness of fibers. The optimized solutions were also analyzed by the proper orthogonal decomposition (POD) to clarify the effects of planform on aerodynamic loads and structural sizing results. The POD successfully identified geometrical modes that correspond to three characteristic planforms in optimized solutions. Furthermore, some preliminary results on data-driven approach for unsteady fluid-structure interaction problems are presented.

Byungjin An (Ebara Corporation)

Data Science Application in Ebara

Technology development to effectively control unsteady flows is an important issue related to our products in terms of implementing new functions and value-added improvement. In order to address the issue, it is necessary to investigate the characteristics of flow and understand them correctly, and theoretical analysis, experiments, and numerical analysis approaches have been carried out conventionally. In recent years, attempts have been actively carried out to apply data science in addition to the conventional methods. We present examples of new approaches to applying data science and discuss the effects of data science on our product and future application development.

Hessam Babaee (University of Pittsburgh)

Reduced-Order Modeling using Time-Dependent Bases with Applications to Turbulent Combustion

Many important problems in fluid mechanics are described by high-dimensional partial differential equations (PDEs). The computational cost of solving these problems using classical discretization techniques increases exponentially with respect to the number of dimensions — a fundamental challenge that is dubbed the curse of dimensionality. On the other hand, many of these high-dimensional problems have a much lower intrinsic dimensionality, that if discovered, can mitigate the curse of dimensionality. This calls for techniques that extract and exploit correlated structures directly from the PDE. This approach is in direct contrast to classical discretization techniques that disregard multidimensional correlations and result in inefficient solutions for high-dimensional problems. While there are numerous data-driven dimension reduction techniques that can extract these correlated structures by solving the full-dimensional PDE, these techniques are only feasible for lower-dimensional PDEs (e.g., 2D/3D). This same workflow is impracticable for many high-dimensional

PDEs as computing the solution of the full-dimensional PDE is the very problem we cannot afford to solve. To this end, we present a reduced-order modeling framework, in which the correlated structures are extracted directly from the PDE — bypassing the need to generate data. These structures are exploited by building on-the-fly reduced-order models (ROM). The correlated structures are represented by a set of time-dependent orthonormal bases and their evolution is prescribed by the physics of the problem. We present several demonstration cases including reduced-order modeling of reactive species transport equation in turbulent combustion as well as sensitivity analysis and uncertainty quantification in fluid dynamics problems.

Jiro Doke (MathWorks)

MATLAB Ecosystem: Teaching Tool in the Field of Data Science

Data science is a field that has become important not just for engineering and science students, but also for students from a broader range of disciplines. In addition, computational thinking, which is one of the foundation skills needed in data science, has been a critical component in education for many years. The MATLAB ecosystem provides tools to help incorporate computational thinking into the classroom. In this session, I will introduce (relatively) recent MATLAB features that can be used in the classroom to enhance the learning experience for the students and to foster computational thinking skills. Live scripts allow instructors to prepare an executable lecture note, that can be further extended by individual students. Interactive controls in live scripts allow students to explore concepts. More sophisticated interactivity can be accomplished through apps. During the COVID pandemic, many instructors have made use of apps to create virtual labs to replace or supplement physical labs. Throughout the session, I will perform in-product demonstrations as well as introduce ready-made educational content provided by MathWorks and the user community.

Koji Fukagata (Keio University)

Reduced Order Modeling and Estimation of Flow Fields Using Convolutional Neural Networks – Towards Machine Learning Assisted Flow Control

Application of machine learning is currently one of the hottest topics in the fluid mechanics field. While machine learning seems to have a great possibility, its limitations should also be clarified. In our group, we have started a research project to construct a nonlinear feature extraction method by applying machine learning technology to "turbulence big data," extracting the nonlinear modes essential to the regeneration mechanism of turbulence and deriving the time evolution equation of those nonlinear modes. In this presentation, we will introduce some examples on learning and regeneration of temporal evolution of cross-sectional velocity field in a turbulent channel flow using convolutional neural network (CNN). We will also introduce the application of CNN for super-resolution analysis and extraction of low-dimensional nonlinear modes for flow around a bluff body accompanying vortex shedding. We also introduce our attempts to interpret the nonlinear modes extracted by CNN autoencoder and to use them for an advanced design of flow control, as well as an attempt for uncertainty quantification and applications to experimental data.
This work was supported by KAKENHI KIBAN (A) (FY2018-2020, No. 18H03758) "Construction of feature extraction method for turbulence big data by machine learning" and JSPS KAKENHI KIBAN (S) (FY2021-2025, No. 21H05007) "Creation and implementation of an innovative flow control paradigm utilizing machine learning" by Japan Society for the Promotion of Science.

Kai Fukami (UCLA)

Reconstructing and Modeling Unsteady Flows with Physics-Inspired Machine Learning

Recent advances in numerical and experimental technologies facilitate access to massive spatio-temporal high-resolution fluid flow data. Machine learning has been recently recognized as a powerful tool to compress such rich high-degree of freedom data into a compact form that retains key features of unsteady flows. This presentation explores the importance of physics-inspired machine learning for global field reconstruction and nonlinear modal reduction of fluid flows. We first present super-resolution analysis, which reconstructs a high-resolution flow field from sparse and low-resolution data, with examples of isotropic turbulence and turbulent channel flow. We find that a physics-inspired neural network that accounts for scale-invariant characteristics of turbulent vortical structures accurately reconstructs the flow field from a low-resolution snapshot. The present super-resolution analysis can further be generalized in on/offline sensor conditions with the assistance of Voronoi tessellation. Our reconstruction techniques are also tested with industrial turbulence examples such as turbulent vortices in a pump sump. These successful reconstructions imply the existence of hidden and important information of the original flow physics in sparse measurements. Additionally, we discuss the use of a physics-guided nonlinear autoencoder to extract a low-dimensional representation of high-dimensional fluid flow dynamics. We apply the present technique to wakes over a NACA0012 airfoil at several angles of attack with gust disturbances to yield an interpretable manifold for a collection of complex wake dynamics which reflects how complex wakes are affected by gust disturbances. Embedding a priori knowledge into machine-learning models enables us to utilize low-dimensional information in understanding and modeling complex fluid flows.

Susumu Goto (Osaka University)

Application of Reservoir Computing to Turbulence

The direct numerical simulation of turbulence at Reynolds number Re generally requires the degrees of freedom proportional to $Re^{9/4}$. Although the majority of this large degrees of freedom is for small-scale fluid motions, we are usually interested only in large-scale flow. This is why the construction of a good turbulence model, in which we only resolve large-scale flow and model small scales, has been a long-standing unsolved issue in the research field of turbulence. In the present study, we deal with this problem using machine learning. More concretely, we use a kind of recurrent neural network (Reservoir Computing) to predict small-scale quantities (e. g. the energy dissipation rate) as a function of large-scale ones (e. g. the kinetic energy) giving a foundation for turbulence modeling. Here, we emphasize that turbulence has small-scale universality. Our recent studies of turbulence through direct numerical simulations have revealed that the universality holds not only in the statistical sense but also in the dynamical sense. In other words, we can transfer the neural network constructed using data at a given condition (e. g. a given Re) to other cases with different flow conditions. In the talk, we will show some successful examples of the application of the Reservoir Computing to turbulence problems. (Collaboration with Masanobu Inubushi and Satoshi Matsumoto)

Hiroshi Gotoda (Tokyo University of Science)

Complex-Systems Analysis of Thermoacoustic Combustion Instability in a Swirl-Stabilized Combustor

Recent advancements of time series analysis based on complex-systems approach have provided an encompassing understanding and interpretation of the dynamic behaviors in complex combustion phenomena [Sujith and Unni, Phys. Fluids 32, 061401 (2020): Sujith and Pawer, Thermoacoustic instability (Springer Series in Synergetics, Springer, 2021)]. The importance of complex-systems approach has been shown by one of the authors in experimental and numerical studies on various combustion phenomena including a buoyancy-driven turbulent fire [Tokami et al., Phys. Rev. E 101, 042214 (2020): Tokami et al., Phys. Rev. E 140, 024218 (2021)], flame front instability in a Hele-Shaw cell [Nomi et al., Phys. Rev. E 103, 022218 (2021): Nomi et al., Chaos 31, 123133 (2021)], and thermoacoustic combustion oscillations [Murayama and Gotoda, Phys. Rev. E 99, 052222 (2019): Hashimoto et al., Phys. Rev. E 99, 032208 (2019): Kobayashi et al., Phys. Rev. Appl. 11, 064034 (2019): Aoki et al., J. Appl. Phys. 127, 224903 (2020): Kurosaka et al., Chaos 31, 073121 (2021): Shima et al., Phys. Fluids 33, 064108 (2021)]. In this workshop, we present the nonlinear dynamics of thermoacoustic combustion oscillations in a swirl-stabilized combustor from the viewpoints of symbolic dynamics and complex networks.

Michael David Graham (University of Wisconsin-Madison)

Data-Driven Manifold Dynamics for Modeling and Control

The success of many machine learning applications is often attributed to the "manifold hypothesis", the idea that many nominally very high-dimensional data sets actually reside on or near a manifold of much lower dimension within the ambient space. In applications such as fluid mechanics that are governed by dissipative PDEs we expect this hypothesis to be strictly valid, as dissipation smooths out small scales leading the long-time dynamics to lie on a finite-dimensional invariant manifold sometimes called the inertial manifold. We describe a data-driven reduced order modeling method that (1) estimates manifold dimension and determines a coordinate representation of the manifold using an autoencoder, and (2) learns an ODE describing the dynamics in these coordinates, using the so-called neural ODE framework. With the ODE representation, data can be widely spaced and no time derivatives of data are required. We apply this framework to chaotic bursting dynamics of Kolmogorov flow and transitional turbulence in plane Couette flow, finding dramatic dimension reduction while still yielding good predictions of short-time trajectories and long-time statistics. This method enables highly efficient and effective design of reinforcement learning control algorithms, as we illustrate with turbulent Couette flow.

An important extension of this approach emerges from the recognition that for a general manifold, no single intrinsic global Cartesian coordinate representation can be found. In the language of topology an "atlas" of overlapping local coordinate representations, or "charts", must be used. We use this framework to represent nonlinear dynamics of dissipative PDEs on manifolds of intrinsic dimension.

Traian Iliescu (Virginia Tech)

ROM Closures and Stabilizations for Turbulent Flows

In this talk, I will survey reduced order model (ROM) closures and stabilizations for under-resolved turbulent flows. Over the past decade, several closure and stabilization strategies have been developed to tackle the ROM inaccuracy in the convection-dominated, under-resolved regime, i.e., when the number of degrees of freedom is too small to capture the complex underlying dynamics. I will present regularized ROMs, which are stabilizations that employ spatial filtering to alleviate the spurious numerical oscillations generally produced by standard ROMs in the convection-dominated, under-resolved regime. I will also survey three classes of ROM closures, i.e., correction terms that increase the ROM accuracy: (i) functional closures, which are based on physical insight; (ii) structural closures, which are developed by using mathematical arguments; and (iii) data-driven closures, which leverage available data. Throughout my talk, I will highlight the impact made by data on classical numerical methods over the past decade. I will also emphasize the role played by physical constraints in data-driven modeling of ROM closures and stabilizations.

Michio Inoue (MathWorks)

MATLAB Ecosystem: Data Science with Open Source and Beyond

Why MATLAB for data science? One answer is its the ecosystem. With the recent updates with the enhanced capabilities, MATLAB streamlines the workflow that includes data-centric preprocessing, model tuning, model compression, model integration, and automatic code generation, even with models developed outside of MATLAB, such as TensorFlow and PyTorch. In particular, easy-to-use apps in data preparation come in handy to support the preparation and labeling of data, including image, video, and audio formats. In this session, I will describe the above features and will also highlight how to leverage the public cloud platforms like Microsoft Azure and Amazon Web Services (AWS) to speed up your data analytics, training, simulation, and deployment workflows. I will demonstrate how you can take full advantage of the ecosystem to do data science.

Anya Jones (University of Maryland)

Towards New Methods of Lift Regularization in Discrete Gusts

Understanding and mitigating a wing's response to gusts and unsteady winds has been a topic of much research over the past decade, but it has only recently been demonstrated in the laboratory that given real-time lift measurements, a closed loop controller can be used to regularize lift transients using pitch actuation. However, modern optimal and robust control techniques are limited by the quality of the model for the system dynamics. Furthermore, in practical applications it is often the case that force measurements are not available, and controllers must instead act on inertial or flow measurements. These challenges present an opportunity to take advantage of recent advances in machine learning and data science to make progress in the discipline of controlling unsteady aerodynamics systems. The UMD gust-enabled towing tank is currently undergoing renovation to make it possible to explore non-traditional control methods for gust alleviation, including reinforcement learning. The model control system will be able to use arbitrary sensor input to explore a set of actions, while exploiting knowledge accumulated through many iterations. Initially, the set of actions will consist of all permissible angle of attack histories and the measurements used will be real-time force signals. As the wing is repeatedly towed through a discrete, large-amplitude transverse gust, the learning agent should discover that no pitch input is required before and after the gust encounter, and that pitching down into the gust and then up out of the gust can result in a much lower lift transient. Future experiments will replace force measurements with input from various types of sensors, prompting the learning agent to discover novel strategies for detecting and mitigating gusts. Importantly, this upgraded experimental facility will make it possible to test different types of algorithms and approaches, facilitating collaboration with other groups with machine learning expertise.

Soshi Kawai (Tohoku University)

Unsupervised Machine-Learning for Super-Resolution and SGS Modeling of Very Coarse-Grid LES

The scale-resolving methods, such as LES, are now essentially replacing the RANS in the academic turbulence research and have increased attention to the industry. For example, thanks to a high-fidelity numerical scheme and wall modeling we developed, we have achieved the LES of full aircraft configurations using up to 50Bn grid points on the supercomputer Fugaku. This study tries to develop the very coarse-grid LES modeling, one of the challenging topics in LES, using machine-learning-based super-resolution to reduce the required grid points for the LES drastically and further accelerate the use of LES in the industry. The key issue here is that the very coarse-grid LES flowfield is not equivalent to the filtered DNS flowfield. In this study, we develop an unsupervised machine-learning (CycleGAN)-based method for the super-resolution reconstruction of the coarse LES flowfield to the DNS quality flowfield to evaluate the SGS stress components for the very coarse-grid LES.

Steve M. Legensky, David A. Amels, Earl P. N. Duque and Atsushi Toyoda (Intelligent Light)

Augmenting DMD and Frequency Analysis with Visualization for Engineering Applications

Engineer's interest in the use of modal analysis techniques such as DMD and machine learning in CFD workflows is increasing. The CFD techniques, for which this analysis is being applied, vary widely; from RANS to URANS to LES, Lattice Boltzmann, and Flux Reconstruction to name a few. Most current data science research activity however, focuses on canonical flows or DNS on simple geometries, rather than on production CFD codes and real geometries with complex boundary conditions. Solver models (such as those for turbulence) and numerical techniques such as mixed order, overset grid systems and limiters can have negative effects on the resulting reduced order and surrogate models. This paper reviews these issues and shares the experiences using frequency (FFT) and DMD analysis to resolve real-world design issues in which specific visualization and space/time sampling methods were used. These methods showed the utility of tools which provided a fusion of DMD/FFT information with CFD results in solving engineering problems.

Rajat Mittal (Johns Hopkins University)

The Force Partitioning Method: A Data-Enabled Method for Dissecting Aerodynamic Forces in Vortex Dominated Flows

Pressure on a body immersed in a flow is induced simultaneously by vortices, acceleration reaction (a.k.a. added mass) effects associated with body and/or flow acceleration, and viscous diffusion of momentum, and determining the relative importance of these different mechanisms remains one of the most important and fundamental issues in fluid dynamics. Pressure-induced drag and lift are key to the performance of wings, rotors and propellers; undulating fins and flapping wings generate pressure-induced forces that are key to locomotion in fish, birds and insects; time-varying aerodynamic forces drive flutter and flow-induced vibrations of flexible structures, and these same forces enable the extraction of energy from flow via devices such as wind-turbines. I will describe the force partitioning method (FPM), a data-enabled method that partitions pressure forces into components due to vorticity, acceleration reaction and viscous diffusion. FPM has been used to gain new insights into a variety of vortex dominated flows including dynamic stall in pitching foils, vortex-induced vibration of bluff-bodies, locomotion of carangiform swimmers and rough-wall boundary layers, and results from these analyses will be presented. Finally, FPM has been extended to aeroacoustics, and applications of the aeroacoustic partitioning method (APM) to dissect aeroacoustic noise in engineering and biological flows will be presented.
Funding from Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO) and National Science Foundation (NSF) is gratefully acknowledged.

Taku Nonomura (Tohoku University)

Advanced Fluid Measurement based on Active Use of Modal Decomposition

In this presentation, recent advanced fluid measurement based on active use of modal decomposition will be introduced. One is sparse processing particle image velocimetry (SPPIV) for real time estimation of flow fields. This technique uses proper orthogonal decomposition (POD), optimized processing point selection in the particle image velocimetry (PIV), and a Kalman filter, and achieves 2000 Hz real time flow observation of 10 m/s flow around airfoil. The other is spatio-temporal superresolution of supersonic flow. This technique combines the microphone data of high temporal but low spatial resolution and the PIV data of low temporal but high spatial resolution by reduced-order model, and the flow data of high temporal and spatial resolution is estimated. Those techniques pioneer the new frontier of the advanced fluid measurements.

Fortunato Nucera (Honda R&D)

GAN-Based Automobile Flow Field Prediction from Simple Geometric Data

The exciting improvement in hardware performances (specifically GPU and TPU) and the rising demand for fast prediction and generative systems has triggered, in the past decade, a renovated interest in the field of deep neural networks and has led to the development of Generative Adversarial Networks (GAN) in 2014. GANs have therefore been deployed on tasks related to super resolution, Image-to-Image translation, and even hyper-realistic deepfakes. At the same time, due in part to the advent of EV vehicles, the automotive industry has become more competitive and fast design and engineering are now essential. It is in this framework that several attempts have been made to switch from aerodynamic simulation through CFD to prediction via neural networks. In literature, the typical flow field prediction system relies on some geometric preparation (commonly, voxelization) and an approximation model - typically very deep Convolutional Neural Networks (CNNs) - with a final Mean-Squared-Error (MSE) loss on the target data. We argue that this fully data-driven approach is insufficient, as it purely relies on distributional summary statistics, without taking into account the nature of the matter of interest (aerodynamics). In our work, we contend the necessity of the inclusion of the residuals of the Navier-Stokes equations within the loss function in order for the prediction model to pass a CFD expert inspection (the analogue of a visual Turing test for classification). In addition, we employ a traditional Generator/Discriminator GAN architecture where each of the components is a deep CNN. We demonstrate the generalizability of the results through training on a set of morphed spheres of the size of a soccer ball with the associated Large Eddy Simulation (LES) results and prediction on an automobile shape, and draw conclusions regarding the performance of the prediction system and its possible future improvements.

Kie Okabayashi (Osaka University)

Preliminary Study on Learning and Test Modes of Data-driven Cavitation Model

The goal of this study is to develop a "data-driven cavitation model" based on a machine learning model that is trained by the measurement data, rather than a conventional mathematical model, as a breakthrough in the development of cavitation models. We also aim to improve the model by the data assimilation aspect of using measured data. As a preliminary study, this report attempts to develop a framework for a data-driven cavitation model using CFD data calculated by a homogeneous fluid model. The goal in this case is to obtain a data-driven cavitation model that reproduces the homogeneous fluid model. The target is cavitating turbulent flow around a Clark-Y11.7% hydrofoil with an angle of attack of 0°. The machine learning model is U-Net, which is a kind of convolutional neural network used for object detection. The training dataset consists of the velocity, pressure, and liquid volume fraction fields of the current step as input data and the liquid volume fraction field of the next step as the training data. The training results show that U-Net is generally able to predict the volume fraction of the liquid of the next step. However, the error from the CFD result is relatively large at the trailing edge of the hydrofoil, where unsteady behaviors such as detached vortices and cloud cavitation occur. Therefore, considering the implementation of the data-driven model into CFD, it is necessary to change the loss function for emphasizing these unsteady phenomena, or to use a machine learning model with higher prediction accuracy.
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Kunihiko Taira (UCLA)

Toward Extreme Aerodynamics with Data-Driven Approaches

Data-driven methods are indispensable tools for complex physical problems that are challenging for traditional theoretical, experimental, and computational techniques. This is especially true for complex dynamics without an established model and those that provide an extremely large amount of data over a vastly different set of parameters. The aerodynamics of flying vehicles in extreme levels of disturbances falls into such a category of physical problems due to the strong nonlinearity and enormously large combinations of disturbance parameters to consider. As external disturbances in the atmosphere, in urban canyons, or over mountainous terrains hit flying bodies, the interacting dynamics between the disturbance and the wake can exert transient forces that can render standard flight control approaches ineffective. The present study aims to extract the key dynamics from such aerodynamic scenarios from a large number of numerical simulations using machine learning-based techniques. One of the challenging aspects of extreme aerodynamic problems is the complete lack of theoretical foundation and a unified perspective. In this talk, we will discuss our ongoing efforts to understand extreme aerodynamics and develop novel data-driven approaches to analyze, model, and control the violent behaviors of these turbulent flows. (This work is supported by the Vannevar Bush Faculty Fellowship and the Air Force Office of Scientific Research.)

Tomoaki Tatsukawa, Kozo Fujii (Tokyo University of Science)

Preliminary Study of Extraction of Speed-Control Strategy in En-Route Air Traffic using Multi-Objective Optimization and Machine Learning

Although air traffic demand is temporarily decreased due to COVID-19, it is expected to grow in the following decades, causing the overcapacity of large-scale airports. In this study, we attempts to extract the optimal speed control strategies in response to the target airport and airspace for air traffic controllers. As a case study, this study focuses on the arrival traffics at Tokyo International Airport (RJTT). Combining the rule-based simulator and the multi-objective optimization, the cruise speed of 432 target flights corresponding to the design variables are controlled at 150 NM from RJTT for the purpose of minimizing flight duration of both the cruise flights and the pop-up flights. As the data exploration technique, the decision trees for two main traffic flows are constructed to classify the speed control target. The target variable is the binary value converted from the design variables of non-dominated solutions whereas the explanatory variables are the air traffic information obtained at the moment of the speed control. As a result, the constructed decision trees output the significant features such as the separation and the congestion and the corresponding threshold values varying in accordance with each route cluster. This result suggests that our approach has the potential to help air traffic controllers to automatically select the speed control target regardless of airport and airspace.

Aiko Yakeno (Tohoku University)

Challenges for Delaying Transition to Reduce Airplane Drag

Reducing drag of an aircraft continues to be one of the most important research issues in the field of fluid engineering. Drag reduction technology by "laminarization" is one of the essential technologies for next-generation passenger aircraft, and our laboratory is promoting joint research with multiple companies such as MHI and JAXA. The transition mechanism at the leading edge of the swept main wing of the passenger aircraft has not been clarified so far. In our study, we succeeded in large-scale flow computation at the practical cruising state, and showed that generation of the transitional coherent-modes is explained by the energy transient amplification in a short target time (Yakeno and Obayashi, Physics of Fluids (2021)). We also made innovative proposals that overturn the conventional concept of "surface roughness -> increases drag", such as demonstrating flow simulation over rough surfaces (Tameike et al. Journal of Fluid Science and Technology (2021), Hamada et al. Proc. of TSFP conference (2022)).

Chi-An Yeh (North Carolina State University)

Data-Enhanced Resolvent Analysis of Turbulent Flows

Resolvent analysis has become an indispensable tool in characterizing, modeling, and control of turbulent fluid flows. Given a statistically stationary turbulent flow, resolvent analysis provides a linear framework to analyze the input-output characteristics of the mean flow to reveal the most amplified flow structures and the associated forcing input over a range of frequencies. Despite its powerful capability, the computational cost of resolvent analysis can become intractable for multi-dimensional flows at high Reynolds numbers. In this talk, we will discuss our efforts on incorporating toolsets from data science and network science to study turbulent flows and guide active flow control design. In particular, we will highlight the use of randomized numerical linear algebra and hierarchically semi-separable matrix representation to extend the applicability of resolvent analysis for highly complex turbulent flows. We will also see how the resolvent analysis resembles the Katz centrality in the network science so it can be extended to the studies of time-varying base flows. This talk will also provide an outlook of remaining challenges in further enhancing the capability of resolvent analysis. We will address the issues arise from unstable linear operators and discuss available solutions, such as exponential discounting and eddy viscosity models. We will also provide an overview on how the nonlinear forcing can be modeled to reflect the color of the nonlinear forcing and discuss the opportunities of data science techniques in modeling the nonlinear forcing.