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PhD Thesis offer

Title : Machine-Learning based finite volume method for compressible fluid dynamics

Ref. : **SNA-DAAA-2022-21**	
Start date : October 2022	**Application deadline :** May 2022

Keywords: machine learning, neural networks, computational fluid dynamics, finite volume methods, data-driven discretization, hyperbolic conservation laws, compressible Euler equations

Profile: M.Sc. in Applied Mathematics, Mechanics, Data Science or related discipline, with excellent academic records.

Skills: Computational Mechanics, numerical analysis of PDEs, machine learning. Programming skills and motivation to learn are required

Context and objectives: ONERA develops and guides research activities in the aerospace field with the objective of disseminating, in collaboration with authorities or organizations responsible for scientific and technical research, research results at national and international levels, promoting their use by the aerospace industry. The Aerodynamics Aeroelasticity Acoustics department (DAAA [1]) specifically prepares technological responses for the benefit of industry to improve aircraft performances and addresses issues of competitiveness as well as societal, environmental and defense needs.

In this PhD project, we are interested in the improvement of numerical simulations (i.e., faster, more robust and more accurate) of compressible flows through the use of machine learning (ML) techniques, in particular artificial neural networks (ANN). Recent works based on either multilayer perceptron, or convolutional neural networks highlight the potential benefits of such techniques when used on PDEs with regular solutions [3-7] and have been recently studied at ONERA [8,9]. We are more specifically interested in using ANN in place of the discretization scheme or some of its components in the context of an unstructured finite-volume (FV) solver for aerodynamics [2]. The ANN will learn from reference solutions obtained on fine grids with the objective to satisfy similar accuracy and efficiency on coarser grids. Attention will be also paid to the theoretical properties of the resulting numerical scheme in terms of convergence, stability, robustness, and efficiency.

Description of work: In order to attain the objectives of the PhD thesis, we propose to divide the work into two main parts :

1. The project will begin by exploring the applicability of ML-based methods for solving numerically hyperbolic PDEs (the 1D inviscid Burgers equation and the 1D compressible Euler equations) and by developing a prototype code based on FV methods. The successful candidate will start by carrying out a literature review of the latest ML-based techniques which aim at accelerating and improving the accuracy of solvers used on different fields of computational mechanics. The candidate will also identify which parts of the numerical scheme are best suited to apply ML-based enhancements in order to improve and speed up classical numerical schemes (slope reconstruction, stabilization, time integration, etc.).

2. In a second step, the successful candidate will implement and test the most promising methods on a 2D FV code for computational fluid dynamics (CFD). This code will have a similar structure to that of the flagship CFD solvers designed at ONERA. It will rely on a more advanced formulation allowing to handle complex geometries, advanced numerical schemes and boundary conditions. Using this code, the successful candidate will be able to analyze in depth the ANN-enhanced method's theoretical properties as well as its ability to capture on coarse meshes the phenomena occurring on high resolution input data. Comparison of the proposed method's accuracy and speed-up will be done with respect to standard numerical methods used in legacy solvers.

During both steps, the PhD candidate will investigate:

- Acceleration of the training phase of the ANN by using either externally, or internally developed tools (backward propagation, gradient descent method, etc.);

- Compatibility of the method with unstructured grids and other numerical schemes (FV methods of different accuracy, discontinuous finite elements methods);
- Compatibility of the formulation with the High Performance Computing (HPC) frameworks used within the in-house developed solvers;
- Analysis of the properties of the ANN-based numerical scheme (consistency, conservation, accuracy, robustness, stability, etc.);
- Explore ways to impose constraints on the ANN to ensure crucial solver properties such as conservation, robustness, stability, and accuracy of the scheme.

Numerical experiments on use cases of increasing complexity will be conducted to assess the ANN-based numerical methods. Results will lead to publications in journals and scientific conferences.

Bibliography:

[1] https://www.onera.fr/en/daaa

[2] http://elsa.onera.fr/

[3] Y. Bar-Sinai, S. Hoyer, J. Hickey, M.P. Brenner, Learning data-driven discretizations for partial differential equations, Proceedings of the National Academy of Sciences, 116 (2019), 15344-15349.

[4] J. Zhuang, D. Kochkov, Y. Bar-Sinai, M.P. Brenner, Learned discretizations for passive scalar advection in a two-dimensional turbulent flow, Phys. Rev. Fluids, 6 (2021), 064605.

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[6] X. Jin, S. Cai, H. Li and G. E. Karniadakis, NSFnets (Navier-Stokes flow nets): Physics-informed neural networks for the incompressible Navier-Stokes equations, J. Comput. Phys., 426 (2021), 109951.

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[9] B. Fanizza, A neural network based artificial dissipation for a high-order approximation of the compressible Euler equations, ONERA DAAA internship, 2021.

Collaborations:

- P. Chinesta of ENSAM Paris : thesis co-director.
- P. Mirowski of Google Deepmind London : thesis co-supervisor (to be confirmed).
- Ongoing collaboration between DAAA and Google AI Paris.

Host Department/Lab at ONERA

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