PhD Studentship proposal

Title : Improving Variational Multiscale models using artificial neural networks for the accurate Large-Eddy Simulation of turbulent flows

Reference : **MFE-DAAA-2021-10**

Starting date: late 2021/early 2022 | **Application closure date:** December 2021

Keywords

Large-Eddy Simulation, Machine Learning, Discontinuous Galerkin methods, Variational Multiscale Simulation

Presentation, context and objectives

In the context of high fidelity simulations of turbulent flows related to aeronautical applications, Large-Eddy Simulation (LES) techniques constitute powerful tools that explicitly characterize the spatial and temporal dynamics of turbulent eddies for a fraction of the computational cost associated to Direct Numerical Simulations (DNS) which aim at representing the full extent of turbulent scales. However, this approach comes with the necessity of modeling the energy transfers between resolved and unresolved (or subgrid) scales, described by the so-called subgrid tensor. In this particular context, Machine Learning approaches present a strong interest to improve the prediction of the subgrid tensor from resolved variables compared to existing subgrid models (see *Beck et al, J. Comput. Phys. 2019*).

The proposed PhD work will focus on developing a new subgrid model inspired by the VMS approach (for Variational Multiscale Simulation, *Hughes Phys. Fluids 2001*), which aims at representing accurately the interscale energy transfers modeled as a spectral eddy viscosity. The classic VMS formulation relies on the scale separation of the LES solution in two parts, respectively characterizing large and small resolved scales, and the application of a dissipative operator to the solution components representing the small scales only, which approximates a spectral-eddy viscosity behavior (concept introduced by *Kraichnan, J. Atmos. Sci., 1976*). In this case the scale separation is driven by an empirical partition number which determines the proportion of large and small resolved scales. The present proposal will generalize this approach by introducing N scales and N model coefficients, where N is the size of the functional basis in which the numerical solution is expressed. Doing so will increase significantly the number of model parameters, but will also provide a greater flexibility for an accurate tuning of the spectral eddy viscosity shape. These coefficients will be provided by an artificial neural network (ANN) from inputs based on the LES solution. The VMS-ANN will be trained from DNS simulations, for which the input (LES solution obtained from filtered DNS fields) and output (model coefficients computed from the knowledge of the subgrid information extracted from the DNS) data is known.

The numerical method considered for developing the new subgrid model is a modal Discontinuous Galerkin scheme, which provides a natural scale separation operator based on the expression of the solution in a hierarchical polynomial basis. Galerkin projection also offers a natural way to implement the VMS operators, and the classic VMS formulation has already been developed and adapted to DG methods at ONERA (*Chapelier et al. CMAME 2016*). DG methods also provide a strong interest for complex applications due to their ability to provide a high accuracy on irregular and polyhedral unstructured meshes, their compact stencil and related low amount of MPI communications makes them suitable to High Performance Computing which is an important characteristic as turbulent flows simulations involve a large number of spatial and temporal degrees of freedom.

PhD work description and planning

The DG-VMS-ANN methodology will be established from the 3D Navier-Stokes equations. The DG/VMS formulation extended to N scales will first be devised, then a code managing projection and filtering operators will be created in order to exchange information between the DNS and DG/hp LES discretizations in order to extract the input solution field and the associated output model coefficients. An artificial neural network will then be trained to provide VMS coefficients as a function of the modes characterizing the DG-LES solution. The data considered to extract the input and output fields and train the models will consist in several configurations of canonical free-shear and wall-bounded turbulence. Several parameters will be considered in the neural network training, such as the type of mesh elements considered, the polynomial degree of the DG approximation or the inclusion of the dissipative terms of the DG discretization in the calculation of the coefficients. First *a priori* validations of the new models will be conducted on hidden data sets, then the models established during the course of the PhD work will be implemented and validated *a posteriori* for aeronautical configurations of interest, such as turbulent jets or flows around airfoils. This last step will be carried out in the CODA flow solver, developed jointly by Airbus, ONERA and the DLR.

This PhD work will be associated with the European research project HiFi-TURB (High-Fidelity LES/DNS data for innovative turbulence models).

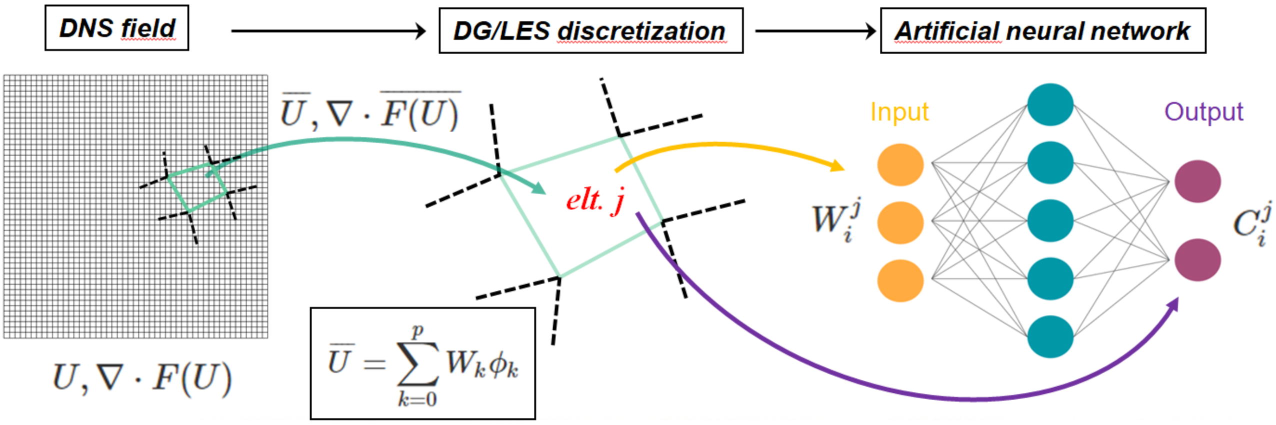

Illustration of the artificial neural network training methodology, with *Wi* the polynomial coefficients associated to the LES solution and *Ci* the coefficients defining the VMS spectral eddy viscosity

References

Beck, A., Flad D. & Munz C.-D. (2019). Deep neural networks for data-driven LES closure models. *Journal of Computational Physics.*

Chapelier, J. B., De La Llave Plata, M., & Lamballais, E. (2016). Development of a multiscale LES model in the context of a modal discontinuous Galerkin method. *Computer Methods in Applied Mechanics and Engineering*

Hughes, T. J., Oberai, A. A., & Mazzei, L. (2001). Large eddy simulation of turbulent channel flows by the variational multiscale method. *Physics of fluids*

Kraichnan, R. H. (1976). Eddy viscosity in two and three dimensions. *Journal of the atmospheric sciences*

Profile: strong background and interest in turbulence modeling and numerical methods for CFD. Notions of machine learning techniques are a plus. Programming languages: Python/C++

Hosting ONERA laboratory:

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