Enhancement of RANS turbulence models by machine learning techniques

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Overview

Turbulence

Predicting the motion of a turbulent flow has many use in aerodynamics, meteorology, etc. however the current approaches and models available today are not have limitation either in accuracy or computational time (if even possible at all).

CFD approaches

Three of these approaches are:

- **DNS**: solves unsteady motion of all scales in the turbulent flow, computationally expensive
- **LES**: solves the large unsteady features in the turbulent flow and model the small scale eddies
- **RANS equations**: model taking account of the enhanced mixing and diffusion induced by the turbulent nature of the flow, computationally inexpensive

Aim, Approach, and Novelty

The aim is to show the performance of machine learning methods applied to improve predictions by the Reynolds-Averaged Navier — Stokes (RANS) equation models of key features for multiple canonical turbulent flow cases.

ML technique to enhance the RANS model performance in flows around bodies will be used.

The novelty of this research is the use of state-of-the-art approach on a diverse range of turbulent flow cases (including new cases in comparison with the previous studies).

Governing equation

Differential equation that governs the mean-velocity and pressure field:

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{1}{\rho} \cdot \frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j^2} \tag{1}$$

where u is the velocity and ρ is the density.
From (1) is derived the RANS equation:

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j} \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho} \cdot \frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j^2} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

using the equality $u_i = \overline{u_i} + u_i'$

Reynolds-stress tensor

The Boussinesq hypothesis gives the Reynolds-stress tensor as:

$$\tau_{ij} = \frac{2}{3} \cdot k\delta_{ij} - 2\nu_t S_{ij} \tag{3}$$

k: turbulent kinetic energy
S_{ij}: strain-rate tensor
ν_t: turbulence viscosity.

Using the previous equations we obtain numerical solution for the flow case studied however for turbulent cases the solution will probably be inaccurate therefore the need of improving it using Machine Learning.

Neural Networks

Multiple types of NN that can improve RANS models exist.

- Feed-Forward NN
- Recurrent NN
- Convolutional NN

Their goal is to minimize the discrepancy between the training data and the truth result that is known, this is done via the introduction of a cost function J, however these types of NN have different architectures.

Field Inversion ML

The specificity of FIML is the introduction of a corrector β parameter into the cost function. Therefore we have the corrected cost function $J_c(\beta)$, however to prevent over correction it also penalizes for large value of β.

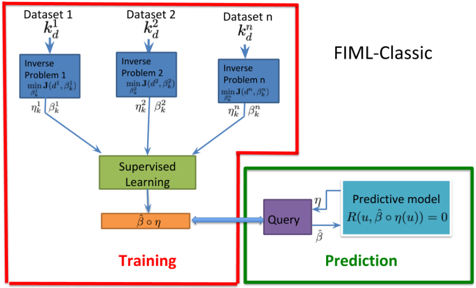


Figure: Flowchart of the FIML-classic approach

Methodology

The methodology is composed of 6 steps followed by evaluation and comparison of the results.

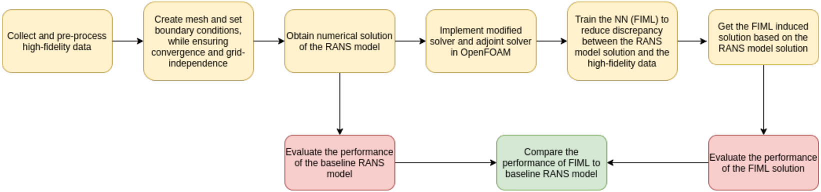


Figure: Flowchart of the methodology

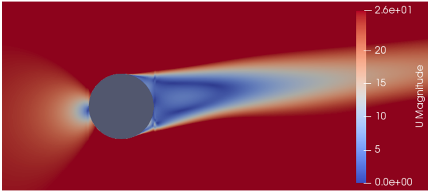
Cases and Data sets

- Turbulent Near Wake Of A Circular Cylinder
  https://torroja.dmt.upm.es/turbdata/agard/chapter8/CMP10/
- Airfoil Boundary Layer and Wake
  http://cfd.mace.manchester.ac.uk/ercoftac/doku.php?id=cases:case011
- Normally-Impinging Jet from a Circular Nozzle
  http://cfd.mace.manchester.ac.uk/ercoftac/doku.php?id=cases:case025#description

- CANTWELL B., COLES D. An Experimental Study of Entrainment and Transport in the Turbulent Near Wake of a Circular Cylinder // J. Fluid Mech. 1983. Vol. 136. P. 321-374.
- NAKAYAMA A. Characteristics of the flow around conventional and supercritical airfoils //J. Fluid Mech. 1985. Vol. 160. P. 155.
- Cooper D., Jackson D.C., Launder B.E., Liao G.X. Impinging jet studies for turbulence model assessment. Part I: Flow-field experiments //Int. J. Heat Mass Transfer. 1993. Vol. 36. P. 2675-2684.

Current results

Unsteady and steady RANS computation of the flow around a cylinder are done:



Work in progress

- Computation of the RANS equations solution with grid-independence and convergence.
- Research on modifications of solvers.
- Research on implementation of adjoint solver.