A proposal for automated turbulence modeling

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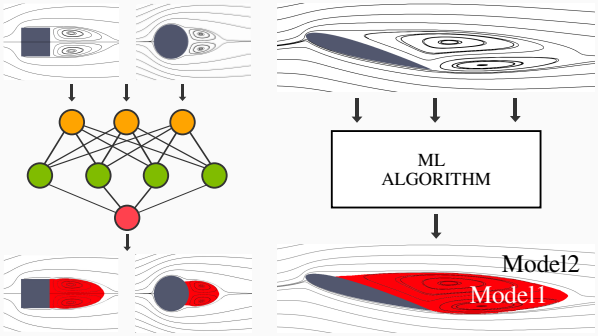

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RANS models limitations

Eddy viscosity models are the most used for RANS closure

$$\overline{u_i' u_j'} = -\nu_t \frac{\partial \overline{u_i}}{\partial x_j}$$

Eddy viscosity models:

- resemble constitutive relation of laminar flow
- lack physical ground and generality
- are contaminated by the quest for universality

RANS models and ML

Prevailing approach

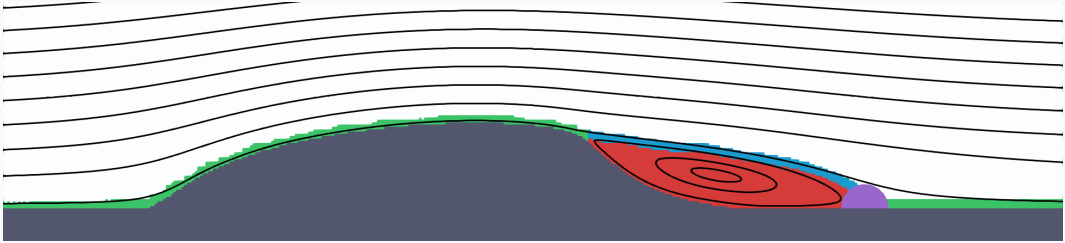
- ML as alternative to existing models
- Model PDE are avoided
- Prediction of Reynolds stresses
- High fidelity dataset needed
- Driven by data

Our approach

- ML as complement to existing models
- Model PDE are used
- Prediction of flow zones
- High fidelity dataset not needed
- Driven by physics

Zonal turbulence model

- Modeling each flow zone independently!
- Dates back decades ago: e.g., Avva, AIAA 1998



Zonal Automated Turbulence Modeling (ATM)

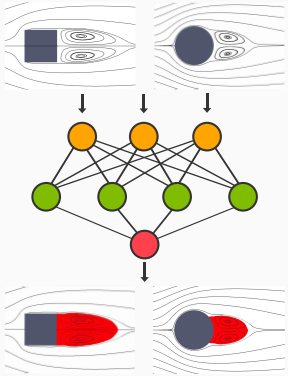
1. Conceptual design

Selection of:

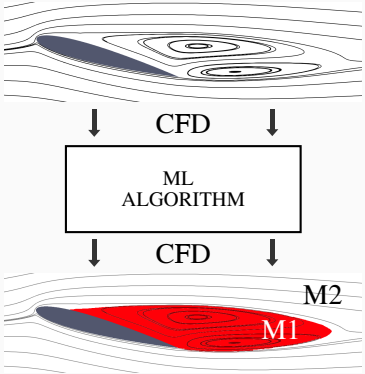
a) Dictionary of flow zones

b) RANS model associated to each zone

2. NN for segmentation



3. Zonal ATM



1. Conceptual design: a preliminary implementation

In this work the conceptual design is kept to a minimun:

a) Extremely short dictionary: only two-dimensional flows, three zones

b) Pure blending of three (existing) models

However, the procedure can be enriched at will.

2. NN for segmentation

ML algorithm for segmentation:

- state-of-the-art U-net

➤ fully convolutional NN

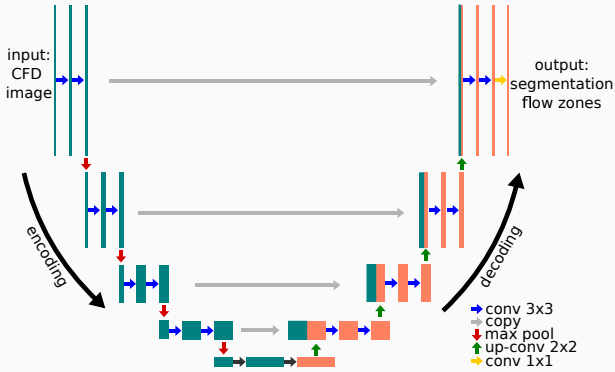
➤ designed for image segmentation

Input:

- CFD solution as an image
- channels with velocity components

Output:

- flow zones segmentation



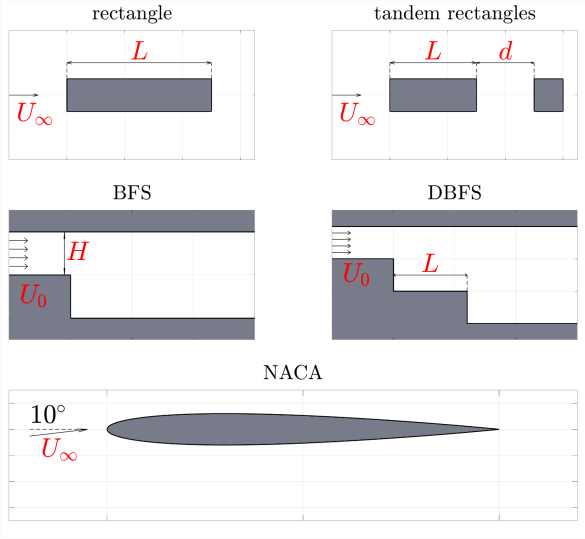
The training dataset

Five classes of 2D steady laminar simulations:

- FreeFem++
- A total of 166 simulations

Dataset generated varying:

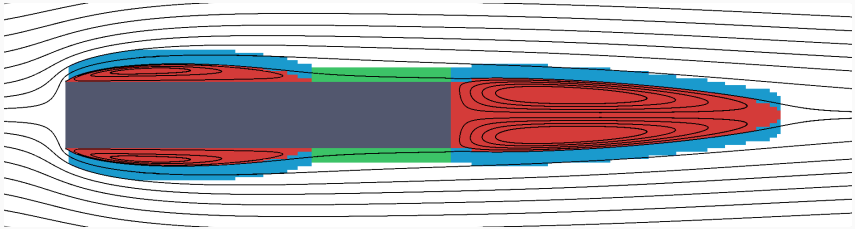
- Reynolds number
- Geometrical features



The labels

Images are labeled manually

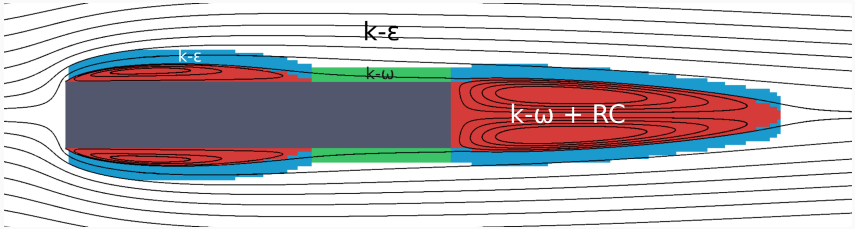
- Flow recirculation → stream function
- Forward attached boundary layer → velocity and streamlines
- Shear layer above flow recirculation → velocity and streamlines
- Solid body (grey)
- Featureless background (white)



3. ATM

Association between zones and RANS models:

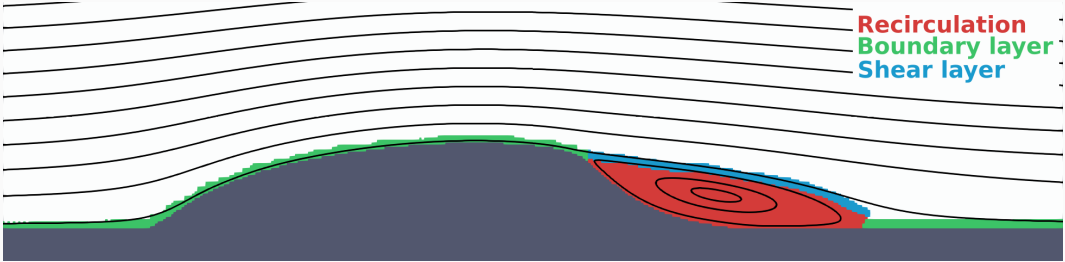
- Flow recirculation $\rightarrow k - \omega +$ Hellsten's Rotation Correction
- Forward attached boundary layer $\rightarrow k - \omega$
- Shear layer above flow recirculation $\rightarrow k - \epsilon$
- Solid body (grey) $\rightarrow -$
- Featureless background (white) $\rightarrow k - \epsilon$



A test case

ATM tested on a separated flow: an hump in a channel.

- Reference: experimental data of Greenblatt *et al.* AIAA 2006
- $Re_c = U_0 c/\nu = 936000$, based on hump 'chord' c



ATM versus established models

model	ΔX_r
$k-\epsilon$	$+8.8\%$
$k-\omega$	$+7.3\%$
$k-\omega$ SST	$+11.3\%$
ATM	$+1.9\%$

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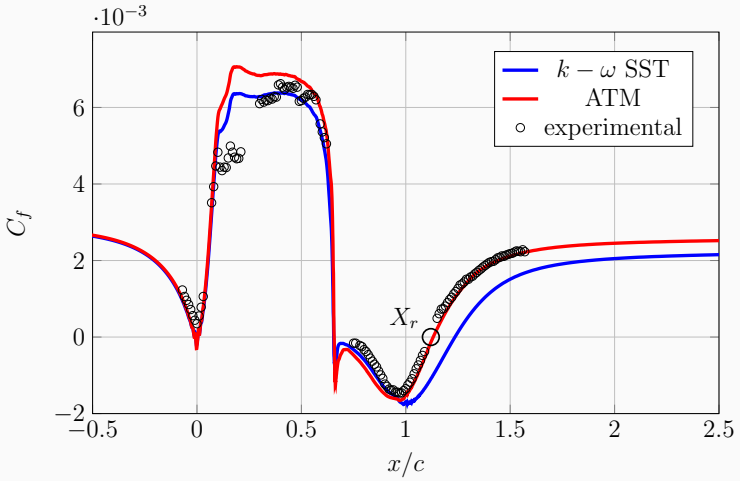

ATM usability

ATM ticks all boxes in Spalart (arXiv, 2023):

- ✓ Zonal model without user input
- ✓ Galilean invariance
- ✓ Publishability of ATM: less than $100Mb$ of data
- ✓ Straightforward integration of the NN within a solver

Conclusions

ML can be leveraged for a better use of existing models:

- Classic eddy viscosity models are not trashed
- The segmentation NN is reliable
- Workflow is feasible

However, understanding the true potential of the ATM approach requires:

1. Enlarging the dictionary of flow zones
2. Choosing the best model for each zone

Zonal Automated Turbulence Modeling (ATM)