TU Clausthal

Neural Network-based Detection of Taylor Vortices in Annular Flow Systems

Exposé for Master Thesis - Initial Presentation

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Contents

Turbulent Flows and Vortices

- Vortical formations are crucial components in the dynamics of turbulence, contributing to processes such as the generation of turbulence, amplification of mass, heat, and momentum transport.
- A vortex is characterized by swiriling motion of fluid around a central region.
- Translating this feature into a formal definition is challenging.

”A vortex exists when instantaneous streamlines mapped onto a plane normal to the vortex core exhibit a roughly circular or spiral pattern, when viewed from a reference frame moving with the center of the vortex core.”

Taylor-Couette flow

- a Fluid dynamic phenomenon that occurs when a fluid is passing between two coaxial-rotating cylinders.
- Inner cylinder is typically rotating faster than outer cylinder.
- Dimensionless control parameters like Re, ω_{inner} and ω_{outer} are key factors

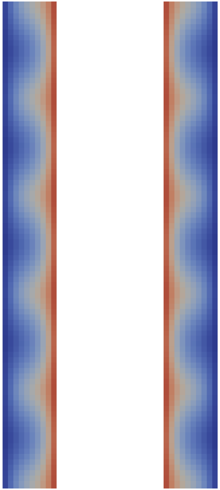


Abbildung: Taylor-couette flow at time-step 19

Vortex Detection Algorithems

- Vortex identificaion methods are categorized into 3 taxonomies:
  - **Region**/**Line**
  - **Eulerian**/**Lagrangian**.
  - **Local**/**Global**.
- One of widely used algorithms is λ_2 method:
  - $\nabla\overline{u}$ is decomposed into *symmetric*(S) and *anti-symmetric*(Ω) parts.
  - three eigenvalues of $S^2 + \Omega^2$ to be calculated.
  - A point int the velocity field is a part of vortex core if at least 2 of them are negative i.e. $\lambda_2 < 0$

Objectives

- Governing equ:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f} \tag{1}$$

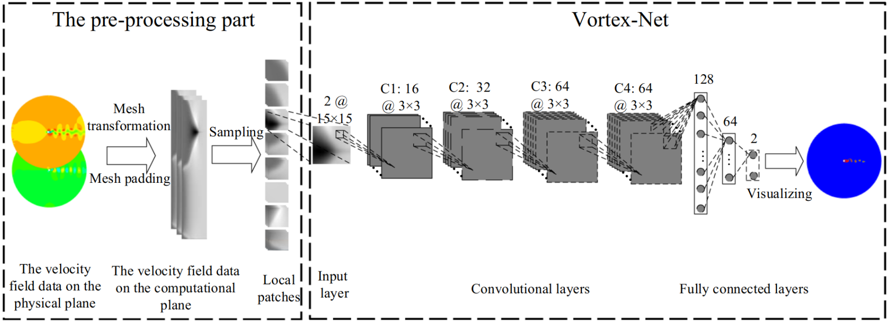
- w.r.t boundary condition:

$$\mathbf{u}(\mathbf{x} + \mathbf{L}) = \mathbf{u}(\mathbf{x}), \tag{2}$$

where $\mathbf{L}$ is the periodicity vector

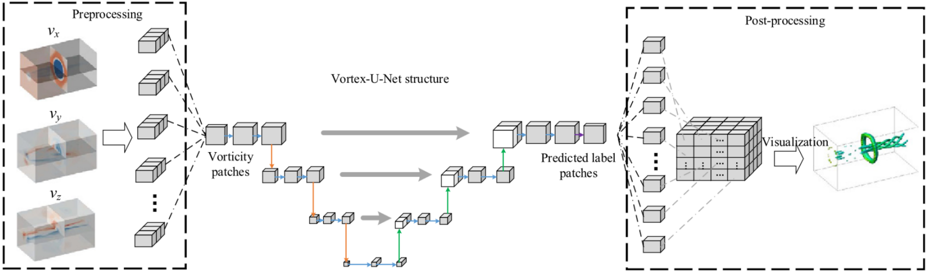
Litrature Review

(a) (Liang et al., 2018), a CNN-based vortex identification method to use both local and global information of flow field.



Litrature Review

(b) (Deng et al., 2022), replacing the fully-connected NN with a segmented network to reduce the computational complexity.



Approach

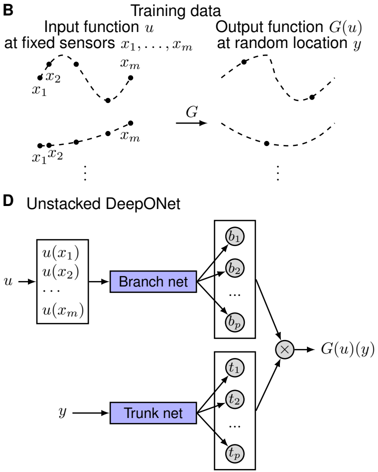
(a) Data preparation:

- Running the *Taylor-couette* case for different values of $\{\omega_{inner}, \omega_{outer}, Re\}$
- Collecting the velocity fields and λ_2 vectors for all time steps.
- Data augmentation techniques (Berenjkoub, Chen & Günther, 2020) like *Linear Transformation* can be used, to compensate the lack of training data.

(b) Model development:

- Trying to Learn the mapping from a function in field to λ_2 method for detecting vortices.
- The objective of trained network is to perform a classification based on the predicted λ_2 values.

Deep operator networks(Lu, Jin, Pang, Zhang & Karniadakis, 2021) (DeepONets)



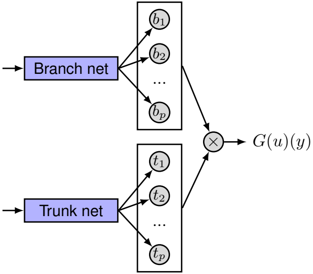
- Each input function u is evaluated at fixed sensor points $\{x_1, x_2, \ldots, x_m\}$
- y with d components and $u(x_i)$ for $i = 1, 2, \ldots, m$ are not matched. Therefor, it is needed to use two subnets. **Branch** for encoding input function at sensor points - **Trunk** for the location to evaluate output function

$$G(u)(y) \approx \sum_{k=1}^{p} b_k t_k + b_0 \qquad (3)$$

Deep operator networks (DeepONets): prediction of λ_2

Inputs of branch:
$\mathbf{u} \in \mathbb{R}^3$, $(N_s,\ 3)$
Outputs of branch:
$\boldsymbol{b} \in \mathbb{R}^{N_f}$, $(N_s,\ N_f)$

Inputs of trunk:
$\mathbf{X} \in \mathbb{R}^{128000}$, $(128000,\ 3)$
Outputs of trunk:
$\boldsymbol{t} \in \mathbb{R}^{N_f}$, $(128000,\ N_f)$

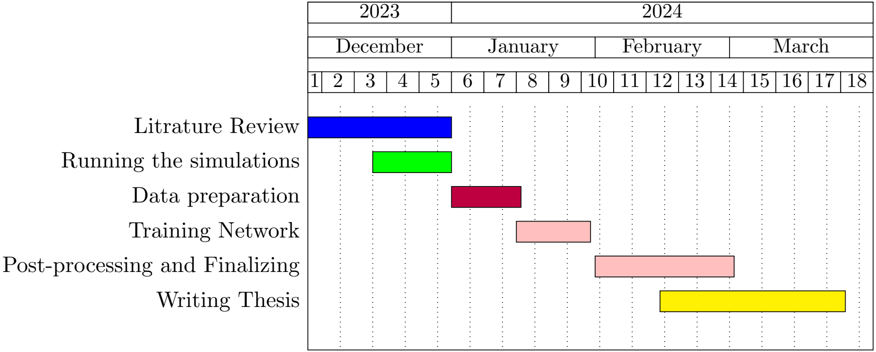


Outputs:
$\boldsymbol{\lambda_2} \in \mathbb{R}^{1\times 128000}$,
$(N_s,\ N_f) \otimes (128000,\ N_f)^T$

Motivation

- Learning the λ_2 operator for detecting vortices within a field.
- Replacing the Finit-Element mothods with NN-surrogate model
- Elinimate the need for manual detection of vortices in flow system using visualization

Timeline


2023
2024
December
January
February
March
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Litrature Review
Running the simulations
Data preparation
Training Network
Post-processing and Finalizing
Writing Thesis

Thank you!

Any questions?

Berenjkoub, M., Chen, G. & Günther, T. (2020, 10). Vortex boundary identification using convolutional neural network.. doi: 10.1109/VIS47514.2020.00059

Deng, L., Bao, W., Wang, Y., Yang, Z., Zhao, D., Wang, F., . . . Guo, Y. (2022). Vortex-u-net: An efficient and effective vortex detection approach based on u-net structure. *Applied Soft Computing*, *115*, 108229. Zugriff auf `https://www.sciencedirect.com/science/article/pii/S1568494621010620` doi: https://doi.org/10.1016/j.asoc.2021.108229

Liang, D., Wang, Y., Liu, Y., Wang, F., Li, S. & Liu, J. (2018, 10). A cnn-based vortex identification method. *Journal of Visualization*, *22*. doi: 10.1007/s12650-018-0523-1

Lu, L., Jin, P., Pang, G., Zhang, Z. & Karniadakis, G. E. (2021). Learning nonlinear operators via DeepONet based on the universal approximation theorem of operators. *Nature Machine Intelligence*, *3* (3), 218–229.