Reduced-Order Modeling of Ship Airwakes with Atmospheric Turbulence Effects using Dynamic Graph Networks

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Why yet another ROM?

Ideal airwake model for helicopter/ship dynamic interface:
- Generalizable: Applicable to parametrized operating conditions and configurations
- Computationally efficient: Fast enough for real-time prediction
- Provides an interface to interact with the flow field of rotorcraft
- Accounts for inflow turbulence with strong stochasticity

More Physics

Model Calibration, Field-Inversion w/ DL
- Purely Physics-based
- ★★★
- Unrealistic

More Data
Dynamic Graph Network

① Convert Eulerian data to a Lagrangian representation (vortices)
② Learn the vortical interaction under Lagrangian frame
③ Map back to Eulerian flow field from Lagrangian solutions

High-Fidelity Training Data on Simple Configurations

Aerodynamic Analysis of Practical Complex Configurations

Graph Representation of Vortex Dynamics

Current State

Future State

Attached vortex
Free Vortex
Graph Neural Network
DGN Architecture

Encoder-Processor-Decoder:
- Vortical states mapped to latent space as embeddings.
- Graph convolution with message passing architecture to aggregate neighborhood embeddings.
- Aggregated embeddings decoded to the desired output.

\[
\mathbf{p}_i^{(k+1)} = \mathbf{p}_i^{(k)} + \Delta t \dot{\mathbf{p}}_i^{(k)}
\]

Implementation:
- Network architecture implemented with PyTorch Geometric (PyG)[1]
- Dynamic graph constructed KDTree in Scikit-Learn [2]
- Encoder and decoder with multilayer perceptrons (MLPs)
- Message passing by 10 ChebConv layers [3]
- Size of latent vector = 128, PReLU non-linear activation.

\[
L(\mathcal{W}) = \sum_{i=1}^{N_k} \sum_{k=1}^{N_t} \left\| \mathbf{p}_i^{(k)} - F(\mathbf{p}_i^{(k)}, \mathcal{G}(k), g^{(k)}; \mathcal{W}) \right\|^2
\]
Demonstration of DGN with 2D Vortex Problem

Three types of error measures

- One-step error:
  \[
  E_1^{(k)} = \frac{1}{N_p} \sum_{i=1}^{N_p} \| \ddot{p}_i^{(k)} - \dot{p}_i^{(k)} \|
  \]

- Rollout error:
  \[
  E_2^{(k)} = \frac{1}{DN_p} \sum_{i=1}^{N_p} \| \ddot{p}_i^{(k)} - p_i^{(k)} \|
  \]

- Single trajectory error:
  \[
  E_3^i = \frac{1}{T_L} \sum_{k=1}^{T} \| \ddot{p}_i^{(k)} - p_i^{(k)} \|
  \]

\( \ddot{p}_i^{(k)} \) is the predicted change of states at time k, which is used to compute new predicted states,
\( \ddot{p}_i^{(k+1)} = \ddot{p}_i^{(k+1)} + \Delta t \ddot{p}_i^{(k)} \)

\( D \): distance between initial and terminal position.
\( L \): total length of the entire trajectory of one particle.
Demonstration of DGN with 2D Vortex Problem

Table 2  Results for 2D vortex cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Time averaged one-step error ($\times 10^{-8}$)</th>
<th>Rollout error at final time (%)</th>
<th>Maximum single trajectory error (%)</th>
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<tr>
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<td>2.11</td>
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<tr>
<td>3</td>
<td>1.91</td>
<td>12.51</td>
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</tbody>
</table>
CFD-based Ship Airwake Simulation

Atmospheric Boundary Layer (ABL) data:
- Mean wind speed of 21.5 m/s, west to east
- Used as initial and inlet condition for ship airwake simulation.
- Simulated using the Simulator for Wind Farm Application (SOWFA)[4] in OpenFOAM[5].

Ship airwake simulation:
- Immersed boundary method (IBM) [6]
Lagrangian Representation and Synthesized Data

3-stage procedure to generate the Lagrangian representation:

- **Detection** of potential vortices
  - \( Q = \frac{1}{2} (||\Omega||^2 - ||S||^2) > 0 \)

- **Clustering** of vortical blobs
  - DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm[7]

- **Characterization** of a generalized vortex
  - Identified clusters characterized by total vorticity, centroid, and anisotropic elongation

Synthesis of 2D Airwake-like Data:

- CFD snapshots as initial condition
- Particle trajectories in between snapshots simulated
DGN Performance on Synthesized Ship Airwake

10 training cases and 3 testing cases:
- Domain starts immediately after ship location
- Less than 1% accumulated rollout error
- Less accurate in wake region

Prediction errors on all synthesized shipwake cases

![Graph showing errors for training and testing cases](chart.png)
Summary of Findings

• High-fidelity CFD Simulation
  o Ship airwakes with atmospheric turbulence effects.
  o Lagrangian representation of the flow field with vortex particles.

• Dynamic Graph Network based ROM
  o 2D vortex problem.
  o Synthesized ship airwake based on CFD snapshots.

• Demonstrated DGN’s capability to
  o Capture the complex turbulent flow phenomena presented in CFD.
  o Extrapolate robustly over unseen data.
  o Generalize with unseen initial condition and perform accurate time series prediction.

• Potential Application
  o Two-way coupled simulation of helicopter/ship dynamic interface modeling in real time.
  o Full scale 3D ship airwake problem.
Thank you.

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Reference


