Development of CFD Model for Hydrodynamic Prediction of a Horizontal Tidal Current Turbine

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OUTLINE

- Introduction
- Fully Resolved CFD Method
- Cartesian Grid Method with ACL Model
- Conclusion
Introduction

Tidal Energy

- Higher Energy density
- More predictable than random wind energy
- Large scale power generation

- NEDO project of Japan (From 2014)
  Kyushu Univ. & Kawasaki H. I. Ltd.
**Purpose:**
- Develop CFD tools for simulation of tidal farm with the consideration of interference among multiple turbines

**Objectives:**
- Hydrodynamic behavior of a turbine operating in the wake
- Optimization of turbine arrangement
- Estimate the output of the power plant in a tidal period

**Our Tool**

OpenFOAM

*The Open Source CFD Toolbox*

Tidal turbine farm simulation (RIAM, Kyushu Univ.)
■ Fully Resolved CFD Method

For single/multiple turbine simulation
**Numerical Method**

1. **Multiple Reference Frame (MRF)**  Steady state simulation

   The Multiple Reference Frame model computes fluid flow using both the rotating and stationary reference frame.
   - Rotating zone is solved in the rotating frame
   - Stationary zone is solved in the stationary frame

   **Governing equations for steady state**

   Rotating zone:
   $$(u_R \cdot \nabla) u - \Omega \times u = -\nabla p + \nabla \cdot \left( u_{eff} (\nabla u + (\nabla u)^T) \right)$$
   \[ \nabla \cdot u_R = 0 \]

2. **Sliding Mesh**  Transient simulation

<table>
<thead>
<tr>
<th>Only Rotating Region</th>
<th>Include Stationary Region(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady</td>
<td>SimpleFoam + <strong>MRF</strong> options</td>
</tr>
<tr>
<td>Transient</td>
<td>pimpleDyMFoam + sliding mesh</td>
</tr>
</tbody>
</table>

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1. Single Turbine – Southampton U model


- Smooth transition for a stable computation
- Renumber mesh to minimize matrix band width

<table>
<thead>
<tr>
<th>Current Speed (m/s)</th>
<th>Rotation Speed (rad/s)</th>
<th>TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>1.4</td>
<td>17.5</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>6</td>
</tr>
<tr>
<td>1.4</td>
<td>24.5</td>
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<td>1.4</td>
<td>28</td>
<td>8</td>
</tr>
<tr>
<td>1.4</td>
<td>31.5</td>
<td>9</td>
</tr>
</tbody>
</table>

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Vortex structure (by Q-criterion)

Limited Streamlines
Setting angle (5-deg)

Flow Separation

Fully resolved CFD method

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Fully resolved CFD method

0-deg pitch angle: Thrust and Power Coefficients

\[ C_P = \frac{Q \Omega}{(1/2) \rho U_0^3 A} \], \quad \frac{C_T}{T} = \frac{T}{(1/2) \rho U_0^2 A} \]

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Commercial BEM code (GH-Tidal Bladed)
Academic in-house BEM code (SERG-Tidal)
Exp.: *Bahaj et al., 2007, Southampton Univ.
5-deg pitch angle: Design case

Thrust and Power Coefficients

- Fully resolved CFD method
- Commercial BEM code (GH-Tidal Bladed)
- Academic in-house BEM code (SERG-Tidal)

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10-deg pitch angle:

Thrust and Power Coefficients

- Commercial BEM code (GH-Tidal Bladed)
- Academic in-house BEM code (SERG-Tidal)

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2. Single Turbine - K. H. I. model

- **Turbine Model**
  Rotor diameter: 18m
  Num. of blade: 3
  Speed: 15rpm

- **Domain Setup**
  Rotating center: (0, 0, 0)
  Domain:
  X- dir: -2.5D~6.7D
  Y- dir: -1.5D~1.5D
  Z- dir: -D~2D

- **RAS Computation:**
  k-omega-SST model + AMI sliding mesh treatment + transient solver

- **LES Computation:**
  k-equation eddy-viscosity model + AMI sliding mesh treatment + transient solver
Fully resolved CFD method

Structured Mesh Generation
(Full model)

Grid num.: about 6M
Type: All hexahedron structured grid

Rotating part:
Master patch
Slave patch

Sliding Mesh Treatment

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Fully resolved CFD method

Vortex Structure (Q-criterion)

RANS
K-epsilon

Axial velocity field
3. Multiple Turbine - K. H. I. model

◆ Two Turbine Interference
Distance: H=1.5D
Mesh size: 12M

◆ Computation Capability Estimation
(HPC Cluster in our Lab)
◆ 8 Computing Nodes
◆ 128G Memory per nodes
◆ Total 32 CPUs
◆ Total 256 Physical Cores
◆ Total 1024G Physical Memory

Max. Turbines:
10-12 (Parallel Arrangement)

◆ Limitations (Full resolved method):
- Mesh generation is complex
- Mesh quality is not good in wake region
- Computation capability limitation

Vortex Structure
(Q-criterion)
(RAS: k-omega-SST)
- Cartesian Grid Method with ACL Model

For tidal turbine farm simulation
ACL Method: (proposed by Sørensen and Shen*)

Blades discretized into span wise sections of constant airfoil, chord, twist, oncoming current

Airfoil lookup tables used to calculate lift and drag at each actuator section

Force on flow is equal and opposite to blade force

Force is normalized and projected back to N-S Eq.

Vortex structure caused by actuator line

Theory of ACL:

I. Body force calculation in ACL

\[ f_{2D} = \frac{dF}{dA} = \frac{1}{2} \rho U_{rel}^2 c (C_L e_L + C_D e_D) \]

- \( C_L \) and \( C_D \) are the lift and drag coefficients
- \( U_{rel} \) is the local wind velocity
- \( e_L \) and \( e_D \) are the unit vectors in the direction of lift and drag

II. Projected using a convolution:

\[ f_\epsilon = f \otimes \eta_\epsilon \quad \eta_\epsilon = \frac{1}{\epsilon^3 \pi^{3/2}} \exp[-(r/\epsilon)^2] \]

- \( \eta_\epsilon \) is a regularization function
- \( \epsilon \) establishes the width of the function
Cartesian Grid Method with ACL Model

Implementation of ACL:

Combined with the AMR function in OpenFOAM

AMR: Adaptive Mesh Refinement

a. Cartesian grid
b. AMR grid
c. Axial velocity field by AMR grid
d. Vortex structure of Cartesian grid
e. Vortex structure of AMR grid
Cartesian Grid Method with ACL Model

**RANS simulation with ACL**

K-epsilon turbulence model

**Velocity Field**

- TI=1.1%
- TI=15%

**Turbulence kinetic energy (TKE)**

- TI=1.1%
- TI=15%

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Cartesian Grid Method with ACL Model

- Inlet Flow: 3m/s (1/7 power law)
- Hollow: 1.1% TI
- Solid: 15% TI

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LES Simulation with ACL:

Ongoing developments

- Use full developed boundary layer simulation volumetric data to initialize tidal farm domain.
- Use ACL tidal turbine model for turbine simulation.
- Save planes of data in every time step as inflow BC.
- Combined with pitch control, yaw control
- Use Immersed Boundary Method for terrain effect.

Final Goal:
Estimate the power output of a tidal farm

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Tidal Plant Simulation
5-turbines
Uniform upstream (no turbulence)
LES (Smagorinsky model)

Total Mesh Num: 26M
Simulation Time: 0-400s
Computing Time: 6hours
Cores: 100
Conclusion

- CFD development is being carried out, in which OpenFOAM library is applied, for simulation of tidal current turbines.
- A fully resolved CFD method has been developed to predict hydrodynamic performance of one or two turbines.
- A Cartesian grid method with ACL model has been developed to predict turbine wake and tidal turbine farm.
- A physical experiment is planned for validation of the CFD codes.