Experimental Activity and Numerical Modelling of the PoliMi IPC-VAWT Physical Model for Wind Tunnel Tests with Open-Data Purposes

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Presentation overview

- PoliMi Wind Tunnel Facility

- The PoliMi Vertical Axis Wind Turbine with IPC
  - Structural design
  - Mechatronic design
  - Control Hardware/Software features

- Numerical model (Actuator Line)
  - Effective velocity model in OpenFoam
  - Numerical pre-test…

- Conclusions and future developments
PoliMi Wind Tunnel
Facility Overview

1.5 MW
Closed - circuit
Wind Tunnel

Two different
test sections for
different applications
Wind Tunnel Facility

13.8x3.8m, 16m/s,
Boundary Layer Section:
- turbulence < 2%
- with turbulence generators = 25%
- 13m turntable

4x3.8m, 55m/s,
Low Turbulence Section:
- turbulence <0.1%
- open jet / closed test section
Low Turbulence Test Section

13.8x3.8m, 16m/s,
Boundary Layer Section:
- turbulence < 2%
- with turbulence generators = 25%
- 13m turntable

4x3.8m, 55m/s,
Low Turbulence Section:
- turbulence <0.1%
- open jet / closed test section
PoliMi IPC-VAWT
In-house design

Reference machine for VODCA project:
VAWT Open Data for Code Assessment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airfoil</td>
<td>NACA0021</td>
</tr>
<tr>
<td>Chord C</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Height H</td>
<td>2.7 m</td>
</tr>
<tr>
<td>Radius R</td>
<td>1.5 m, 1.0 m</td>
</tr>
<tr>
<td>Blades N</td>
<td>3</td>
</tr>
<tr>
<td>Solidity σ</td>
<td>0.25, 0.375</td>
</tr>
</tbody>
</table>

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Design of structural parts & assembly issues

**Design parameters**
Angular speed: 300 rpm
Radius: 1.5 m
PoliMi IPC-VAWT
Blades

Carbon fiber/composite sandwich structural rib

C=0.25 m

Genetic Algorithm Optimization

Assuming hinged kinematic configuration

\[ w_m = \frac{5}{384} \frac{h^4}{E_c J_{1,x}} (q_c + q_{aer,max}(\theta)) \]

First natural bending frequency, \( n=1 \)

\[ f_n = K_n \left( \frac{n^2 \pi}{2 h^2} \right) \sqrt{\frac{E_c J_{1,x}}{\rho_c A_l}} \]

<table>
<thead>
<tr>
<th>NACA  Airfoil</th>
<th>( t ) (mm)</th>
<th>( 2a_{\text{max}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0012</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>0014</td>
<td>37.5</td>
<td>29</td>
</tr>
<tr>
<td>0018</td>
<td>45</td>
<td>34</td>
</tr>
<tr>
<td>0021</td>
<td>52.5</td>
<td>40</td>
</tr>
</tbody>
</table>
PoliMi IPC-VAWT
Individual Pitch Control unit

Roller bearings
SKF 61911-2RS1

Motor-blade coupling shaft

Elastic joint
GIFLEX GE-T 14 SG

Maxon motor-reducer
EC-4pole 30, brushless, 200W
Encoder MR
Gearhead GP32

'α and β methodology’’ by H. Giberti

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**PoliMi IPC-VAWT Control features**

- **Hollowed Motor**
  - Motor Power: Ska Rotary 245.60

- **Slip Ring Moog** AC6373

- **Main shaft motor**
  - Angular velocity
  - Current (Torque)
  - Analog

- **Main shaft angular velocity and position**
  - Homing
  - Digital

- **1P + NP detector**

- **2 Proximitors** Omron M8x1

- **Controller** Maxon Escon 50/5

- **Blade motor** (angular loop)
  - Angular velocity
  - Current (Torque)
  - Analog

- **Blade angular speed**
  - Homing
  - Digital

- **Encoder Lika Line-Driver**
PoliMi IPC-VAWT
Wind Tunnel test capabilities

Tips Speed Ratio: \( \lambda = \frac{\omega R}{V} \)

<table>
<thead>
<tr>
<th>Radius ( R )</th>
<th>[1.5, 1.0] m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidity ( \sigma )</td>
<td>[0.25, 0.375]</td>
</tr>
<tr>
<td>Wind ( V )</td>
<td>[4 - 20] m/s</td>
</tr>
</tbody>
</table>

\( \omega > 2.5 \) for lower IPC control bandwidth or amplitudes

Main shaft \( \omega \) [Hz]

1P limit due to: A B

Design limit

\[ F_1 = 19.5 \text{ Hz} \]
\[ F_1/3P > 2 \]

Experimental IPC Bandwidth assessment

Max sine wave amplitude without phase shift for
1P = 2.5 Hz
3P = 5 deg

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PoliMi IPC-VAWT
Control tasks

Effective shaft angular position $\vartheta(t)$

$$\vartheta(t) = \vartheta_k + \frac{\vartheta_{k+1} - \vartheta_k}{\Delta T_k}$$

$\vartheta(t)$ = 10°$\sin(\vartheta(t))$
PoliMi IPC-VAWT
Actuator Line Numerical modelling

Fully-resolved airfoil simulations (FRA)

- Geometrical model of the turbine in the computational mesh.
- Resolution of the discretized Navier-Stokes equations.
- The aerodynamic forces on blades computed from the pressure field as a post-processing analysis.

Actuator Line simulations (AL)

- The computational domain does not contain the turbine profile.
- Aerodynamic forces computed analytically from the tabulated aerodynamic coefficients.
- Resolution NSE with explicit added momentum source term

\[ \frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u u) - \nabla \cdot (\mu \nabla u) + \boldsymbol{f} = -\nabla p \]

solve
\{
    fvm::ddt(U) + fvm::div(phi, U) + turbulence->divDevReff(U) + volumeForce == -fvc::grad(p);
\}

\[ \vec{F} = \frac{1}{2} \rho C t h v \sqrt{2} (C_L(\alpha) \vec{l} + C_D(\alpha) \vec{d}) \]
Results

Performance

Parametric study on the 2D config.

IPC, 1P sine waves
different amplitudes

$\phi(t) = \phi_0 \sin(\vartheta(t))$

$\varphi(t) = 0$

2D, AL Vs DMST, different solidities

2D, AL, high solidity, Fixed Vs 1P pitch

3D effects count…

$C_{D,\phi} = C_{D,\phi_0}$

$C_{P,\phi} / C_{P,\phi_0}$

Fixed Pitch $\phi = 0$

$\phi = 5 \cdot \sin(\theta(t))$

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Results
Aerodynamics

Re: 1.5-3.2 E5
Stall: 12-13°
Results
Near wake
Conclusions

- Wind facility
- PoliMi IPC-VAWT
  - Structural and mechatronic design
  - Features
  - Testing conditions
  - OpenFoam/Actuator Line modelling
  - Results: Solidity, 2D/3D, IPC, Wake…→ Experimental validation needed!

Ongoing developments

Experimental

- Wind tunnel performance characterization
- VODCA project: VAWT Open Data for Code Assessment
  - International benchmark for code validation (OC3/OC4/OC5 style)
  - Euromech Kick off meeting on Friday at 1.30 pm, you are all welcome!!

Numerical

- Dynamic stall modelling in OpenFoam
- OpenJet configuration
Thank you!