The application of a wind flow model for intelligent control strategies development and noise prediction for wind turbine operations

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Part I
Wind Turbine Noise

Acknowledgement: Ms. Ping Ma and Dr. Eugene Yee

http://www.youtube.com/watch?v=lm0Oe8J6qT8
• Aerodynamic or mechanical noise
• “Infrasound” and low frequency noise most controversial in terms of health
• Nina Pierpont – Wind Turbine Syndrome
• “We need to stop ignoring the infrasound component of wind turbine noise and find out why it bothers people!” – Alec Salt (2010)

InfraSound: <20Hz
• Low Frequency Noise: 10Hz – 160Hz
• “If you cannot hear a sound … it does not affect you” – Geoff Leventhall (2007)
• “Infrasound … is below the audible threshold and of no consequence” – Geoff Leventhall (2006)
• “No evidence that audible or sub-audible sounds emitted by wind turbines have any direct adverse physiological effects” – David Colby et al. (2009)
Refurbishment of Anechoic chamber at ERC (Energy Research Center)

Sonex Super Foam

<table>
<thead>
<tr>
<th>Octave Band Frequencies (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>NRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>6&quot; Thick</td>
<td>.20</td>
<td>.86</td>
<td>1.22</td>
<td>1.24</td>
<td>1.28</td>
<td>1.24</td>
<td>1.10</td>
</tr>
</tbody>
</table>
Noise reduction method

Muffin XL - MD12B2 - 028868
Vortex Shedding

This is a broad band noise source generated by air separation from the blade surface and trailing edge. It can be controlled somewhat by good blade profile design, proper pitch angle and notched or serrated trailing blade edges.

[Shannon et al., 2005]
Vortex-Control Notches: Smoother Joining

Standard trailing edge:

Trailing Edge with Vortex-Control Notches:

- Leak Flows
- Anti-Vortex Notches

Fan Blade, Vortices, Airflow

www.noctua.at
Wind turbine blades with trailing edge serrations

Acoustic image in dB (decibel)

Oerlemans et al., NLR-TP-2009-401
SIROCCO, Silent Rotors by Acoustic Optimisation (NLR)

≈3.2 dB noise reduction
[rotating source identifier (ROSI)]

≈150 microphones
SAMURAI control windowpane:
- device status information
- device control buttons
- time information
- overload/underflow indicators

Human Vibration Multi Analyzer:
- 3 axial window with sum vector
- filter curves according ISO 2631
- digital and bar graph display
- 3 selectable values per axis

Signal:
- multi channel window
- scrolling & scaleable x-axis
- time signals from all channels
- quick scaling for y-axis

Sonogram:
- single channel window
- FFT- or 1/n octaves spectra
- scrolling & scaleable x-axis
- quick scaling for y- and z-axis

Frequency Analyzer:
- multi channel window
- FFT- or 1/n octaves parallel
- additional sum levels
- linear or log x-axis

NoiseCAM:
- measurement video documentation
- flexible resolution and frame rate
- values of one channel blended-in
- time stamp

Sound Level Meter:
- single channel window with 10 values
- 2 main values additional as bar graphs
- alarm level indicator in one bar graph
- table or level history below bar graphs
Acoustic imaging measurements are limited to frequencies above 100Hz. Blade to tower interactions are briefly noticed.
Acoustic imaging measurements are limited to frequencies above 100Hz.

Blade to tower interactions are briefly noticed.
\[ v_t = F_{RCP}(f_c) C_\mu \frac{k^2}{\varepsilon} \]

RANS: \( F_{RCP}(f_c) \to 1^- \) as \( f_c \to 0^+ \)
DNS: \( F_{RCP}(f_c) \to 0^+ \) as \( f_c \to 1/t_K \)
where \( t_K \) is Kolmogorov time scale

\[
\overline{NS} = \frac{1}{T} \int_0^T NS dt
\]
if \( T \to \infty \), RANS
if \( T \to 0 \), DNS

PRNS: averaging in time,
e.g., \( T = \Delta t \)

LES: averaging in space,
e.g., over \( \Delta = (\Delta x \Delta y \Delta z)^{1/3} \) (space filter width)
Explicit large eddy simulation (LES)

Filtered Navier-Stokes Equations:

\[
\frac{\partial \hat{u}_i}{\partial t} + \frac{\partial \hat{u}_i \hat{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} - \frac{\partial}{\partial x_j} \left[ \overline{u_i u_j - \hat{u}_i \hat{u}_j} \right]
\]

where

\[
\tau_{ij} - \tau_{kk} \delta_{ij} = -\nu_{\text{SGS}} \left( \frac{\partial \hat{u}_i}{\partial x_j} + \frac{\partial \hat{u}_j}{\partial x_i} \right) = -2\nu_{\text{SGS}} S_{ij}
\]

\[
\nu_{\text{SGS}} = C \Delta^2 \sqrt{2S_{ij} S_{ij}}
\]

**Smagorinsky’s constant** either fixed or determined using **dynamic procedure**
Rotor-stator interaction

Ham et al., 2000
CTR summer program

Transitional
Turbulent wake

Ham et al., 2000
CTR summer program
LES with a dynamic model

$t/T = 0$

$t/T = 0.2$

$t/T = 0.4$

Turbulent spots

$t/T = 0.6$

$t/T = 0.8$
Flow over a single cylinder

- Computational domain:

  \[ D = 0.019 \text{m} \quad \text{Re} = 90,000 \]
  \[ \text{Inlet Mach} = 0.2 \]
  \[ 15^\circ \text{C air: } \rho = 1.225 \text{kg/m}^3 \]
  \[ \mu = 1.7894 \times 10^{-5} \text{ kg/m/s} \]
  \[ \Delta t = 3.17 \times 10^{-7} \text{ s} \]

  200,000 \( \Delta t \) before recording

by Ping Ma
$C_1$ variation along time

St number comparison

FLUENT
Receiver located at 90 degree from the free stream direction, **128 D away from the cylinder**
Flow chart

Fluent (static pressure on cylinder surface) → 3D acoustic code (sound pressure fluctuation at receiver’s location) → Matlab FFT (SPL vs. St)

Farassat 1 formulation

Thickness

\[ 4\pi p'(x,t) = 4\pi P_T'(x,t) + 4\pi P_L'(x,t) \]

\[ = \frac{\partial}{\partial t} \left\{ \int_{f=0} \left[ \frac{\rho_0 v_n}{r(1-M_r)} + \frac{p \cos \theta}{cr(1-M_r)} \right] dS \right\} \]

Loading

\[ \text{LES or URANS} \]

retarded time at \( t-r/c \)
Farassat 1A formulation (solution of Ffowcs Williams-Hawkings (FW-H) equation)

\[
4\pi p_T^* (x,t) = \int_{f=0}^{f_{ret}} \left[ \frac{\rho_0 (v_n + v_n')}{r(1-M_r)^2} \right] dS + \int_{f=0}^{f_{ret}} \left[ \frac{\rho_0 v_n \left( r M_r + c(M_r - M^2) \right)}{r^2 (1-M_r)^3} \right] dS
\]

On the surface

\[
4\pi p_L^* (x,t) = \frac{1}{c} \int_{f=0}^{f_{ret}} \left[ \frac{l_r}{r(1-M_r)^2} \right] dS + \int_{f=0}^{f_{ret}} \left[ \frac{l_r - l_M}{r^2 (1-M_r)^2} \right] dS
\]

\[
+ \frac{1}{c} \int_{f=0}^{f_{ret}} \left[ \frac{l_r \left( r M_r + c(M_r - M^2) \right)}{r^2 (1-M_r)^3} \right] dS
\]

Normal velocity of surface moving
Flap (landing configuration)
Noise prediction of a high-lift device


- 13.8 million nodes
- DES (Detached Eddy Simulation)
slat

flap

by Jee-Whan Nam

University of Waterloo
Wind Turbine Blade Comprising a Trailing Edge Flap

[using “piezoelectric smart material”]
The controllable **rubber trailing edge flap** (CRTEF)

- To reduce dynamic load
- Typically combined with pitch control [Madsen et al., 2010 from Denmark]

Flexible trailing edge made of an **elastic material** which can be controlled by means of compressed air or hydraulics
Ffowcs William-Hawkings (FW-H) equation

\[ p'(x,t) = p'^T(x,t) + p'_L(x,t) \]

Arakawa et al. (2005)

Large Eddy Simulation (LES)

Farassat 1A formulation

Observer

Thickness

Loading

Quadrupole

Acoustic analogy

Far-field point

LES for wave propagation
Part II

Pitch Control for Large Wind Turbines using Fuzzy Logic

Acknowledgement: Mr. Simon Qiu and Prof. William Melek
Introduction

- The size of wind turbines has been increased continuously for meeting the demand on clean and renewable energy in the last years. The current largest wind turbine is E126 with 126 meters and 7.0 MW power produced by Enercon.

- For the larger wind turbine, how to reduce the asymmetric and fatigue loads induced by the variable uneven wind is becoming an important issue that is related to the operation reliability and investment cost of wind turbine.
– **Blade pitch control** is applied in this study to enable the wind turbine to **operate more efficiently**:

• To improve the efficiency for variable speed wind turbine;

• To limit and to **protect the wind turbine over the rated wind speed**;

• To **reduce the fatigue load** and to increase the withstand ability of turbine structures without changing the materials, which concept comes from helicopter technology.
To ensure the operation and safety of wind turbine, the status and operation condition of wind turbine are monitored. To that end, the placement of sensors have to be optimized in measuring the dynamic performance of turbines in the structural health monitoring.
Objective

- To study the **fatigue loads** of shaft due to variable uneven **wind-speed-induced asymmetric loads**
- To develop an intelligent collective and individual pitch control system
- To optimize the sensors placement on rotor blades for a large wind turbine [work in progress]
## Individual pitch control

<table>
<thead>
<tr>
<th>Property</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rating</strong></td>
<td><strong>5 MW</strong></td>
</tr>
<tr>
<td><strong>Rotor orient, config.</strong></td>
<td><strong>Upwind, 3 Blades</strong></td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td><strong>Variable Speed, Collective Pitch</strong></td>
</tr>
<tr>
<td><strong>Drivetrain</strong></td>
<td><strong>High Speed, Multi-Stage Gearbox</strong></td>
</tr>
<tr>
<td><strong>Rotor, Hub Dia.</strong></td>
<td><strong>126m, 3m</strong></td>
</tr>
<tr>
<td><strong>Hub Height</strong></td>
<td><strong>90 m</strong></td>
</tr>
<tr>
<td><strong>Cut-In, Rated, Cut-Out Wind Speed</strong></td>
<td><strong>3 m/s, 11.4 m/s, 25 m/s</strong></td>
</tr>
<tr>
<td><strong>Cut-In, Rated Rotor Speed</strong></td>
<td><strong>6.9 rpm, 12.1 rpm</strong></td>
</tr>
<tr>
<td><strong>Rated Tip Speed</strong></td>
<td><strong>80 m/s</strong></td>
</tr>
<tr>
<td><strong>Overhang, Shaft Tilt, Precone</strong></td>
<td><strong>5m, 5°, 2.5°</strong></td>
</tr>
<tr>
<td><strong>Rotor Mass</strong></td>
<td><strong>110,000 kg</strong></td>
</tr>
<tr>
<td><strong>Nacelle Mass</strong></td>
<td><strong>240,000 kg</strong></td>
</tr>
<tr>
<td><strong>Tower Mass</strong></td>
<td><strong>347,460 kg</strong></td>
</tr>
</tbody>
</table>
0 ≤ (\(\beta_{IPC_i} = \Delta \beta_i + \beta_{CPC}\)) ≤ 90°

\(|\beta_{IPC_i}| ≤ 8°/sec\)

\(i = 1, 2, 3\)

Collective pitch control
Hybrid control system
(IPC+IFC)

<table>
<thead>
<tr>
<th>Mean Wind Speed</th>
<th>CPC kNm</th>
<th>IPC kNm</th>
<th>IPC (reduced)</th>
<th>CPC kNm</th>
<th>CPC (reduced)</th>
<th>IPCA kNm</th>
<th>IPCA (reduced)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>2369</td>
<td>2036</td>
<td>-14.0%</td>
<td>1859</td>
<td>-21.54%</td>
<td>1710</td>
<td>-27.81%</td>
</tr>
<tr>
<td>20</td>
<td>2727</td>
<td>2182</td>
<td>-19.98%</td>
<td>2136</td>
<td>-21.68%</td>
<td>1849</td>
<td>-32.19%</td>
</tr>
</tbody>
</table>

PD controller:

\[ \beta_{IFC_i} = -K_p e_i - K_d e_i \]

\[-10^\circ \leq \beta_{IFC_i} \leq 10^\circ, \quad |\beta_{IFC_i}| \leq 100^\circ/\sec\]

Maximize power, minimize bending moment
<table>
<thead>
<tr>
<th>Wilson et al. (2009)</th>
<th>Proposed Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model-based</strong> control approach relied on simplified mathematical models</td>
<td><strong>Rule-based</strong> control applicable to complicated problems</td>
</tr>
<tr>
<td>More suitable for <strong>linear input-output relations</strong> problems and uncomplicated small wind turbines</td>
<td>Applied for <strong>non-linear</strong> complicated problems with parameter uncertainty</td>
</tr>
<tr>
<td><strong>Open loop</strong> control for IPC and no feedback measurements are utilized</td>
<td><strong>Closed loop</strong> control for IPC and measurements of wind load are required to derive pitch control command</td>
</tr>
<tr>
<td>Control performance <strong>highly</strong> dependent on the accuracy of model parameters</td>
<td><strong>Good robustness</strong> in the presence of parameter uncertainty</td>
</tr>
</tbody>
</table>
Enercon E66 wind turbine

- One 1.5 MW Wind Turbine Enercon E66 is located in Dunningen, Germany

- 3-bladed, direct drive, with pitch control
From the inside of the nacelle of E-66

Andreas Rettenmeier, Head of the Endowed Chair of Wind Energy of University of Stuttgart

Simon Qiu
# Technical Specification of E-66

<table>
<thead>
<tr>
<th>Wind Turbine</th>
<th>Enercon E-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed power</td>
<td><strong>1.5 MW</strong></td>
</tr>
<tr>
<td>Hub Height</td>
<td><strong>86 m</strong></td>
</tr>
<tr>
<td>Mean wind speed</td>
<td>5.30 m/s</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>10 – 22 rpm</td>
</tr>
<tr>
<td>Tip speed</td>
<td>36-76 m/s</td>
</tr>
<tr>
<td>Cut in speed</td>
<td>2.5 m/s</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>12.0 m/s</td>
</tr>
<tr>
<td>Cut out speed</td>
<td>28- 34 m/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blade materials</th>
<th>Fibre glass reinforced with Blitz protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter</td>
<td>66 m</td>
</tr>
<tr>
<td>Swept area</td>
<td>3421 m²</td>
</tr>
<tr>
<td>Brake system</td>
<td>- Pitch control</td>
</tr>
<tr>
<td></td>
<td>- Rotor stop brake</td>
</tr>
<tr>
<td></td>
<td>- Rotor locking system</td>
</tr>
</tbody>
</table>
Wind turbines with pitch control techniques

- Construction elements of controlled wind turbine

Schematic diagram of Wind Turbine with Intelligent Control System
Pitch control techniques

- Pitch control aims to limit the power output when the rotor speed is above the rated speed, and to maximize the energy capture when the rotor speed is below the rated speed.

- Pitch control approaches
  - Pitching to stall (fluttering?)
  - Pitching to feather (constant rated power)

From Wind Turbines by E. Hau, Springer 2006
Danish Nibe A

Partially adjustable rotor blade, stalled at 3 different fixed pitch angles
FAST (Fatigue, Aerodynamics, Structure and Turbulence)
Aerodyn

Rotating Annular Streamtube

Based on momentum and blade element (strip) theory

Wake rotation
Plane of rotation

Angle of attack

Lift

Drag

\[ F_\theta \Rightarrow \text{Torque} \Rightarrow \text{Power} \]
FAST program for modeling HAW

Rotation speed (rpm)

Pitch angle
Root bending moment

Blade 1
Blade 2
Blade 3

Root Myb1
Root Myb2
Root Myb3
\[ \Delta M_i = M_i - \bar{M}, \quad \bar{M} = \frac{1}{N} \sum_{i=1}^{N} M_i \]

Blade 1
Blade 2
Blade 3

Variation of blade bending moment, \( \Delta M \)
Let $M_i(v, \beta, t)$ be the objective function for designing the optimal controller.

$$\|\Delta M\|^2 = \sum_{i=1}^{N} \Delta M_i^2, \quad \Delta M_i = M_i - \bar{M}, \quad \bar{M} = \frac{1}{N} \sum_{i=1}^{N} M_i$$

$N$ is the number of blades

The pitch angle should be adjusted in order to minimize the variation of bending moments.

For individual pitch action

$$\Delta \beta_i = f(\Delta M_i(v, t))$$

where $f$ is the function provided by the fuzzy controller.
What is fuzzy logic (FL)?

- Easy way to arrive at a **definite conclusion** based on vague, imprecise, noise inputs
- Incorporate rule-based “**IF X & Y THEN Z**” to solve a control problem rather than attempting to model a system mathematically
- **Robust** and often work first implemented with little or no tuning
- Relying on an operator’s **experience** rather than their technical understanding of the system
- Ideally for **non-linear** system that would be difficult or impossible to model mathematically
Fuzzy variables and **triangular membership function**

Degree of membership (DOM, $\mu$)

**Input 1:** wind speed ($V$)

**Input 2:** variation of bending moment ($\Delta M$)
Degree of membership (DOM, $\mu$)

- Very weak: $\mu_{\text{very weak}} = 0.00$
- Weak: $\mu_{\text{weak}} = 0.00$
- Medium: $\mu_{\text{medium}} = 0.37$
- Strong: $\mu_{\text{strong}} = 0.63$
- Very strong: $\mu_{\text{very strong}} = 0.00$

When $V = 16.0 \text{ m/s}$

- Medium: DOM = 0.37
- Strong: DOM = 0.63

"Fuzzy" variable
## Rule Matrix

<table>
<thead>
<tr>
<th>ΔM</th>
<th>Negative Large</th>
<th>Negative Small</th>
<th>Near Zero</th>
<th>Positive Small</th>
<th>Positive Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Weak</td>
<td>Big Decrease (1)</td>
<td>Decrease (6)</td>
<td>Zero (11)</td>
<td>Increase (16)</td>
<td>Increase (21)</td>
</tr>
<tr>
<td>Weak</td>
<td>Big Decrease (2)</td>
<td>Zero (7)</td>
<td>Zero (12)</td>
<td>Zero (17)</td>
<td>Increase (22)</td>
</tr>
<tr>
<td>Medium</td>
<td>Decrease (3)</td>
<td>Zero (8)</td>
<td>Zero (13)</td>
<td><strong>Zero (18)</strong></td>
<td><strong>Big Increase (23)</strong></td>
</tr>
<tr>
<td>Strong</td>
<td>Decrease (4)</td>
<td>Zero (9)</td>
<td>Zero (14)</td>
<td><strong>Zero (19)</strong></td>
<td><strong>Big Increase (24)</strong></td>
</tr>
<tr>
<td>Very Strong</td>
<td>Decrease (5)</td>
<td>Decrease (10)</td>
<td>Zero (15)</td>
<td>Increase (20)</td>
<td>Big Increase (25)</td>
</tr>
</tbody>
</table>
### Input Membership Function

<table>
<thead>
<tr>
<th>V</th>
<th>ΔM</th>
<th>Δβ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
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<td>2</td>
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<td>3</td>
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<td>24</td>
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<tr>
<td>25</td>
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</tbody>
</table>

### Output Membership Function

-5 to 5 range
velocity (V)

variation of moment (ΔM)

Δβ

16 m/s

500 kNm

Δβ ≈ 1.1°
18: IF (V=M [0.37]) AND (ΔM=PS [0.78]) THEN (Δβ=Z [0.37])
19: IF (V=S [0.63]) AND (ΔM=PS [0.78]) THEN (Δβ=Z [0.63])
23: IF (V=M [0.37]) AND (ΔM=PL [0.22]) THEN (Δβ=BI [0.22])
24: IF (V=S [0.63]) AND (ΔM=PL [0.22]) THEN (Δβ=BI [0.22])

max(0.37,0.78)

Root-Sum-Square (RSS) method

\[
\begin{align*}
Z \text{ (Zero)} &= \sqrt{(0.37)^2 + (0.63)^2} = 0.73 \\
BI \text{ (Big Increase)} &= 0.22
\end{align*}
\]

Defuzzification

\[0.73 \times 0^\circ + 0.22 \times 5^\circ = 1.1^\circ\]
Defuzzification

Degree of membership (DOM)

\[ \Delta \beta \approx 1.1^\circ \]

Output

\( \Delta M \) (input 2)  \( V \) (input 1)
Pitch Control of Rotor Blades using Fuzzy Logic and PID Hybrid Intelligent Technique

Aerodyn or CFD
Work in Progress

• Comparison and verification of the proposed control system with other existing closed-loop control strategies

• Develop **hybrid** intelligent fuzzy control strategies for large wind turbines which utilize both pitch and flap control methods

• Design of turbine **health monitoring system** that utilize **genetic algorithm (GA)** based optimization for identification of ideal sensors placement locations in order to effectively detect structural damages due to excessive loading
Thanks & Questions?