WIND TURBINE TOWER LOAD REDUCTION USING PASSIVE AND SEMI-ACTIVE DAMPERS

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Technical Session:
Innovative concepts and support structures for offshore

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Agenda

• Brief Overview

• Motivation

• Damping devices

• Results

• Conclusions & Future Work
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- Results
- Conclusions & Future Work
Proven and validated technology

• Over 1,600 wind turbines of different generations are in operation
• Concepts are coming from a track record in challenging sites
• A safe design is ensured by measurements and validated simulations
• Components fully tested

Build on the experience of previous WT generations
Product portfolio

**ECO 80 platform**
- **Higher energy yield**
  - Power: 1.67 & 2MW
  - Rotor Ø: 74, 80, 86m
  - Status: ECO74/80: >1’200MW
  - ECO86: Proto 2010

**ECO 100 platform**
- **Higher reliability**
  - Power: 3MW
  - Rotor Ø: 100, 110m
  - Status: ECO100: series
  - ECO110: proto end '09

**Site Average Wind Speed m/s**

**Differentiated and Competitive Products**
ALSTOM PURE TORQUE™ concept

A unique rotor support concept protecting the gearbox from deflection loads

- The hub is resting on a large cast frame on two bearings, transferring all wind deflection loads (red arrows) directly to the tower.
- The shaft is connected to the front part of the hub and inserted inside the large casted frame, transferring only the torque (green arrows) to the gearbox.

Transmitting pure torque to the gearbox for higher reliability.
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Motivation for damping devices

• Next generation WT’s:
  - Longer blades and taller tower
    → larger loads
    → need of integrated designs using structural control.
  - Offshore WT’s
    → costly & difficult access in a rough environment.

• Structural damping → lighter towers and substructures:
  - Decrease costs for material, manufacturing and transportation
  - Fit to manufacturing, installation and transportation limits (weight and geometry)
  - Increase Lifetime of whole turbine

Achieve significant decrease in cost
& reliable, competitive and economical efficient product
Integrated design of structures with embedded control systems

- State-of-the-practice:
  - Tuned Mass Dampers (TMD’s):
  - Multi Tuned Mass Dampers (MTMD’s):
  - Active Mass Damper (AMD):

CHALLENGING !!! → huge mass, large space requirement, prohibitively costly, among many more.

Imaging changing some structural components!!!!

Wide range of innovation available, so the end product is robust & reliable
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Technical description.

Modal damping.

• The tower is a very stiff structure:
  - Small drifts and interstory velocities.
  - The system is non-classically damped $\Rightarrow$ modal properties require complex Eigenvalue analysis.

• Assumption #1: The mode shapes of the non-classically damped structure are identical to those of an undamped structure (ei. $\xi_{nc} = \xi_{ud} = 0.02$).
  - Non-classically damped structure $\Rightarrow$ is not a diagonal matrix due to the complex structure (soil-structure interaction + nacelle & rotor components).
  - The frequency ($\omega$), damping ratios ($\xi$) and mode shapes ($\Phi$) depend on the [M], [K], and [C] matrices.
Technical description.
Magnification factor & effective damping.

• The amount of magnification of the damping force depends on the geometry.

• The device displacements are greater than the structural drift.

\[ u_D = f \cdot u \]

The device displacement \((u_D)\) is proportional to a magnification factor \((f)\) times the structural drift \((u)\).

\[ F = f \cdot F_D \]

The force exerted by the damper \((F)\) on the structure is proportional to the force along the axis of the damper \((F_D)\) times a magnification factor \((f)\).

\[ F_D = C_o \cdot |u(t)|^\alpha \text{sgn}(u(t)) \]

\(C_o\) is the damping coefficient and is the relative velocity between the ends of the damper along its axis.

• Assumption #2: The joints can move up to \(+/-0.3^\circ\) due to slippage distortion and inelastic action during testing.

• Assumption #3: the damper force is reduced by a relaxation time due to sliding at joints.

\[ \tau F_D \]
Damper Geometrical Configurations

- **Diagonal brace**
  
  \[ f = \cos \theta \]

  If \( \theta = 37^\circ \), then \( f = 0.799 \) and consequently \( \xi_D = 0.032 \) or 3.2\% damping

- **Chevron brace**
  
  \[ f = 1 \]

  If \( \theta = 70^\circ \) and \( \psi = 9^\circ \), then \( f = 2.16 \) and consequently \( \xi_D = 0.23 \) or 23\% damping

- **Scissor jack**
  
  \[ f = \frac{\tan \theta}{\cos \psi} \]

  If \( \theta = 70^\circ \) and \( \psi = 9^\circ \), then \( f = 2.16 \) and consequently \( \xi_D = 0.23 \) or 23\% damping

- **Lower toggle**
  
  \[ f = \frac{\sin \theta_1 \sin(\theta_1 + \theta_3)}{\cos(\theta_1 + \theta_2)} \]

  If \( \theta_1 = 32^\circ \), \( \theta_2 = 43^\circ \), and \( \theta_3 = 35^\circ \) then \( f = 2.42 \) and consequently \( \xi_D = 0.2935 \) or 29.35\% damping
Optimal Configuration: Upper-toggle bracing

• Highly efficient configuration that provides high damping.

\[ f = \frac{\sin \theta_2}{\cos(\theta_1 + \theta_2)} \cos(\theta_2 - \theta_1) + \sin(\theta_1) \]

If \( \theta_1 = 30^\circ \), \( \theta_2 = 50^\circ \), and \( \theta_3 = 40^\circ \) then \( f = 2.792 \) and consequently \( \xi_d = 0.39 \) or 39% damping.
Main characteristics

• The damper can be:
  − Passive or active  filled with a viscous fluid or
  − Controllable fluid damper filled with either magnetorheological fluid or electrorheological fluid.

• The damper may be:
  − Dependent of the frequency (passive), current (semi-active), fluid pressure (active), and combined (hybrid).

• Advantages:
  − They dissipate energy over a wide range of deformations and a broad range of frequencies.
  − They are velocity-dependent.
  − Easy manufacturability and assembly on-site.
  − Long-life or high-cycle resistance.

Polar arrangement to provide damping in all directions of the wind turbine due to: (i) rotor movement, (ii) nacelle imbalances.
Geometrical integration (ECO100 t90m - hybrid)
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Control Structure – Feedback Controller +
ACTIVE, SEMIACTIVE & HYBRID TOWER DAMPING
Control scheme

- Semi-active, active, and hybrid control schemes.
- Acceleration and force feedback control.
  - Robust.
  - Optimal.
  - Adaptive and/or predictive.
- Damper force depends on the tower frequency.
- Available sensors, DAC, and processors.
- Power supply from the wind turbine.
- Command signal depends on the device (e.g., for MR damper = current).
Passive – Semi-active damping device
Undamped and damped SF for ECO100 T90 hybrid

Adjusted $\rightarrow$ - 19.8t Hybrid $\rightarrow$ -7.7%

Undamped and damped SF for ECO100 T90 steel

Adjusted $\rightarrow$ - 31.5t Steel $\rightarrow$ -13.1%
Hybrid 90m Tower

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<th>Baseline</th>
<th>Damped</th>
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<th>red.</th>
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<td>3</td>
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Steel 90m Tower

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<th>red.</th>
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Increase Fatigue Safety Factors Tower:

- Hybrid $\rightarrow$ 7.6\% in average, 9\% increase of the lowest
- Steel $\rightarrow$ 11\% in average, 12.5\% increase of the lowest

All values:
- In MNm
- For 1E7 cycles
- 20 years lifetime
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Conclusions

• The impact ➔ significant tower load reduction, consequently the total tower cost may drop (... similar situation for an offshore support structure & tower).

• The advantages ➔ cutting edge technology applied to very high flexible towers and offshore substructures.

• The catch ➔ wind turbine towers and support structures account for a large stake in the total wind turbine cost.
Future Work

Aerodynamic & Gravitational load

Tower base damper location

Hydrodynamic load

Damper locations
Future Work

- Reduce elevated dynamic loads for water depths above 25m

- Increase fatigue life of transition piece connection

- Don’t discard Monopiles as a feasible and cheap substructure solution
  - Cheap manufacturing
  - Cheap installation compared to its substructure counterparts

Consider as a feasible option the Monopile employing dampers for water depths between 5m to 35m
Thank you for your attention!

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WT degrees-of-freedom
External loads

1. Steady:
   1. Mass force: Gravity
   2. Env. Influence: Thrust on the motor, sea current, temperature.
   3. Operational status: Rotational speed

- Transient:
  - Mass force: Breaking forces
  - Env. Influence: Gusts.
  - Operational status: Breaking, grid instabilities

- Periodic:
  - Mass force: Mass imbalance
  - Env. Influence: Tower shadow, wind shear, etc.
  - Operational status: Aerodynamic imbalances

- Stochastic – Random:
  1. Mass force: ~
  2. Env. Influence: Turbulence of wind, sea condition, earthquake.
  3. Operational status: ~
Global Eigenmodes - Tower

1st Tower longitudinal mode

2nd Tower longitudinal mode

1st Tower transverse mode

2nd Tower transverse mode
Global Eigenmodes - Rotor

1st rotor flapwise (out of plane) modes

1st rotor leadwise (on plane) modes
Technical description.
Effective damping.

- Using the Linear Static Procedure (LSP) a velocity-dependent device in a structure may be analyzed.

\[ \xi_D = \xi_S + \frac{1}{4\pi} \sum_{i} W_i \]

\[ W_k = \frac{1}{2} \sum_{i} F_i \delta_i \]

\[ W_j = \frac{2\pi^2}{T} C_j \delta_{ij}^2 \]

Maximum strain energy in the structure, where \( \delta_i \) level displacements and \( F_i \) is the inertia force at the \( i \)th level.

\[ T = \text{the period of vibration of the } k\text{th mode the structure (either FA or StS for a wind turbine);} \]

\( C_j \) is the damping coefficient of the damper \( j \);

\( f_j \) = magnification factor of damper \( j \);

\( W_i \) = is the reactive weight on top of the damping system or at level \( i \);

\( \Phi_{ij} \) = is the relative modal displacement of the damper \( j \) of the \( k\)th vibration mode;

\( \Phi_i \) = is the modal displacement on top of the damping system or at level \( i \).
Elevator Design Restriction
Tower Maximal Force
References


