Assessment of Vortex Induced Vibrations on wind turbines

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Outline

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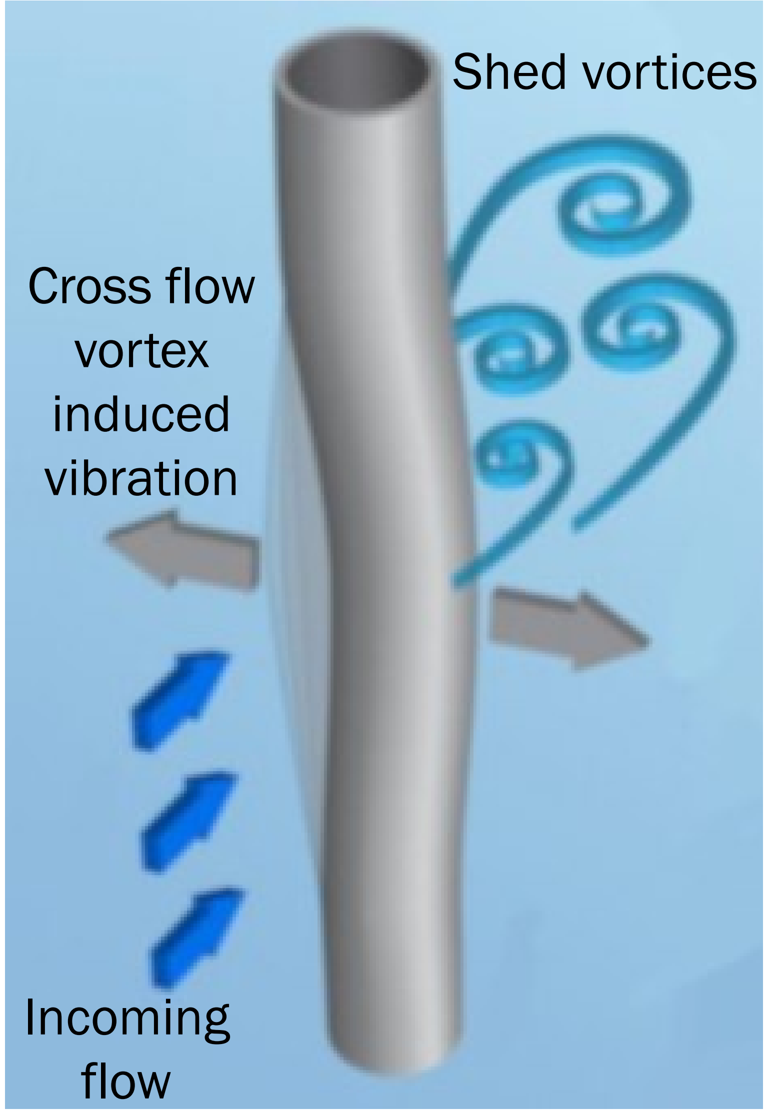
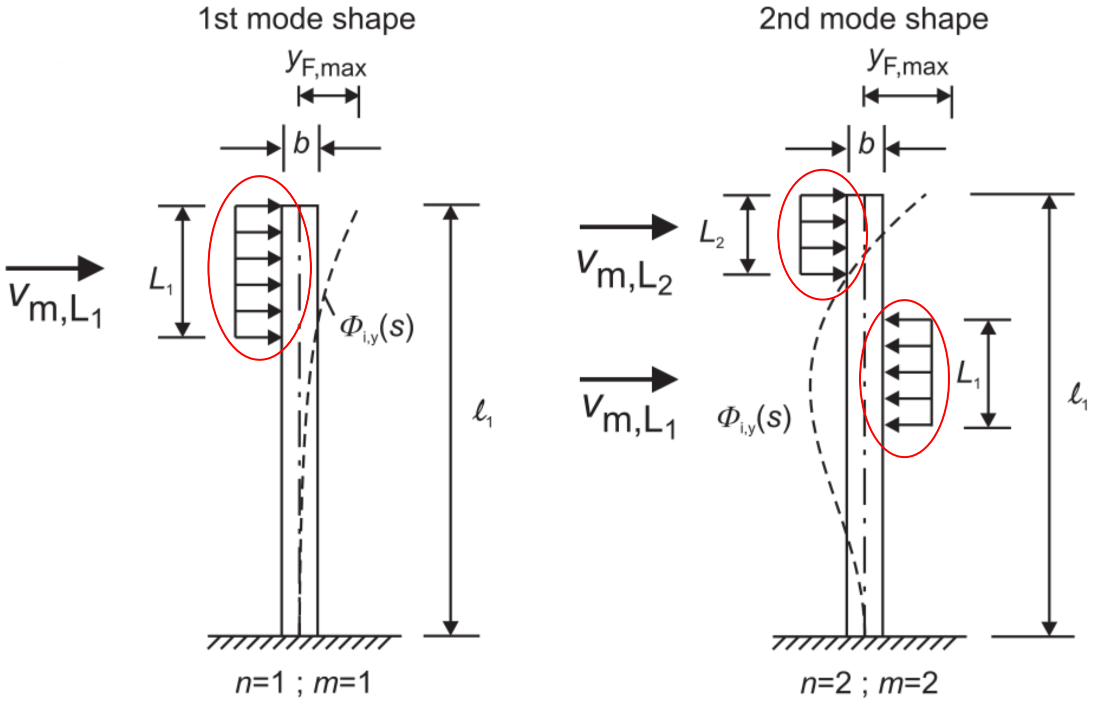
  - ❑ Overview of EUROCODE VIV Approach 1
  - ❑ Enhancements ofVIV Approach 1
  - ❑ Modeling assumptions
- ❑ Numerical results for the NREL 5MW RWT
  - ❑ Modal analysis
  - ❑ Eigenvalue stability analysis
  - ❑ VIV analysis
- ❑ Summary



Overview of EUROCODE VIV Approach 1



Maximum VIV amplitude

$$\frac{y_{max}}{D} = \frac{1}{Sc}\frac{1}{St^2}K_w K \Delta C_L$$

Scruton and Strouhal numbers

$$Sc = \frac{4\pi\xi_i m_{ei}}{\rho D^2}$$

$$St = \frac{D\omega}{2\pi V}$$

Effective correlation length factor

$$K_w = \int_{L_i} |\varphi_i(x)|dx \, / \int_0^l |\varphi_i(x)|dx \leq 0.6$$

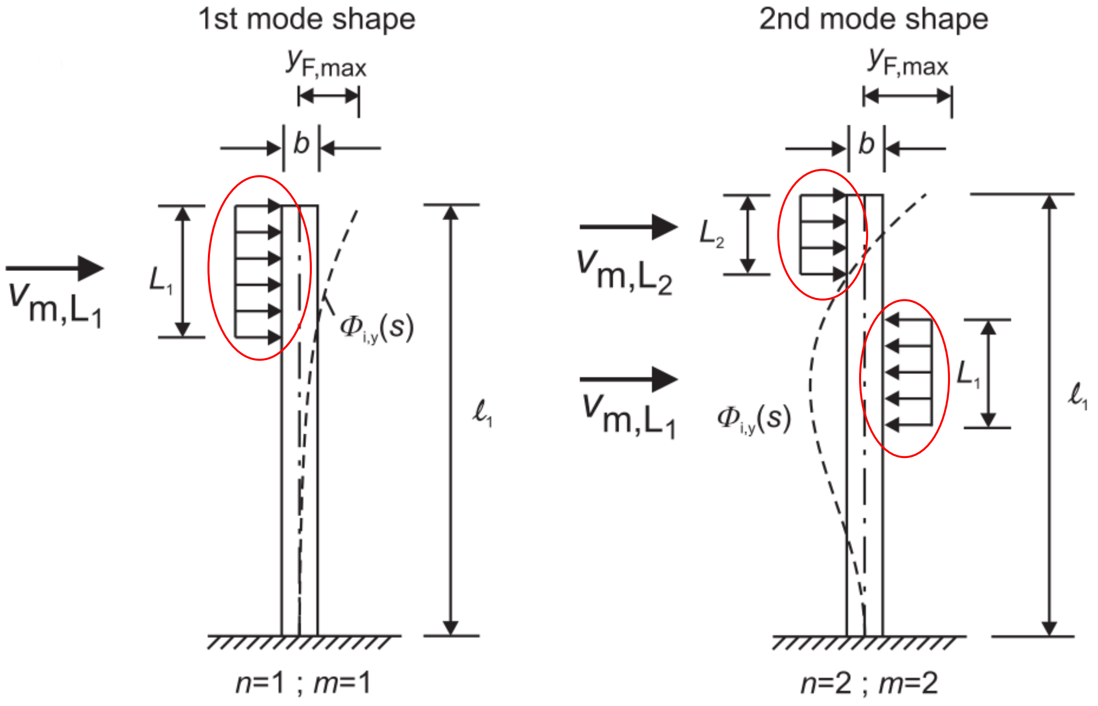
Mode shape factor

$$K = \frac{1}{4\pi}\int_0^l |\varphi_i(x)|dx \, / \int_0^l \varphi_i^2(x)dx$$

Equivalent mass per unit length

$$m_{ei} = \int_0^l m(x)\varphi_i^2(x)dx \, / \int_0^l \varphi_i^2(x)dx$$

Overview of EUROCODE VIV Approach 1



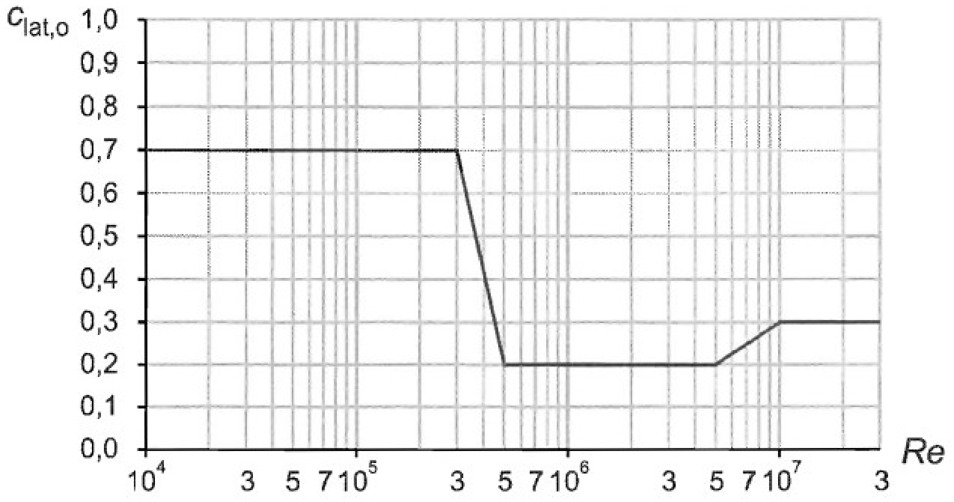
Maximum VIV amplitude

$$\frac{y_{max}}{D} = \frac{1}{Sc}\frac{1}{St^2}K_w K \Delta C_L$$

Semi-empirical framework (defines L_i, ΔC_L and St)

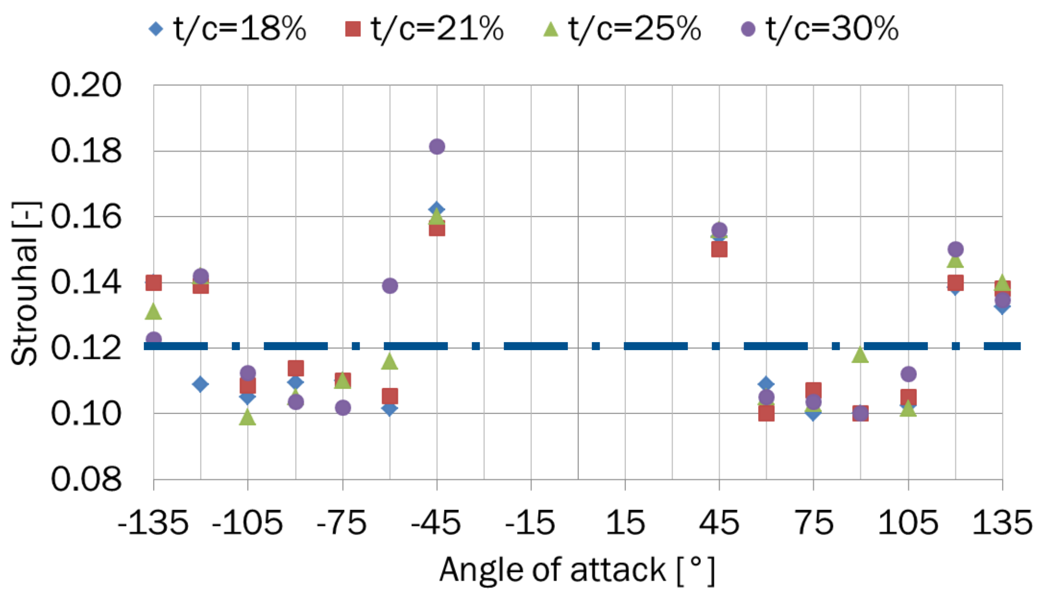
y_i/D	L_i/D
< 0.1	6
0.1–0.6	Interpolation
> 0.6	12

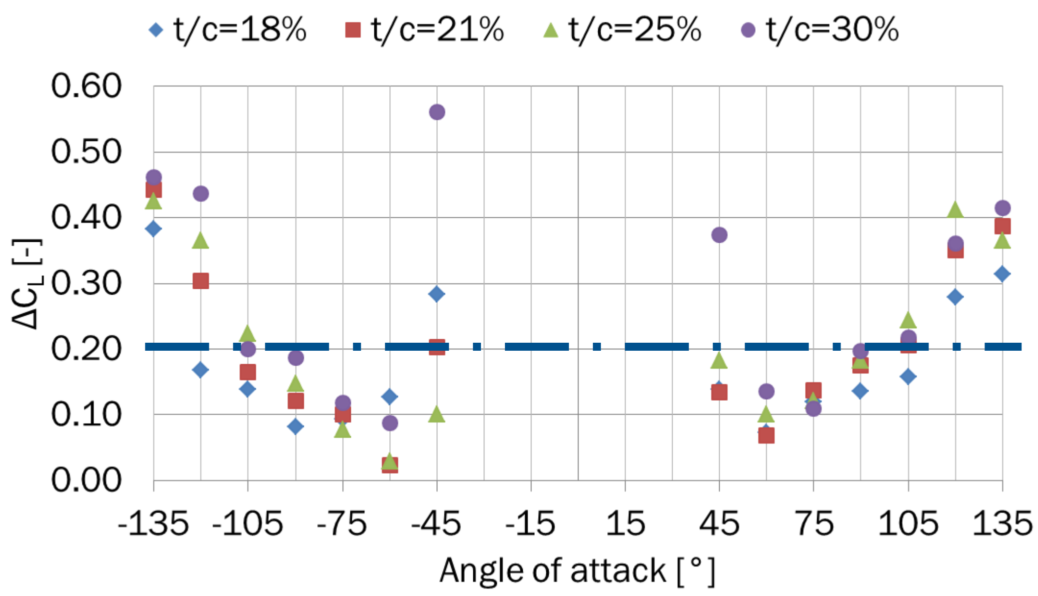
ΔC_L of circular cross section (tower)



Strouhal and Lift Amplitude

2D aerodynamic simulations with free wake vortex code





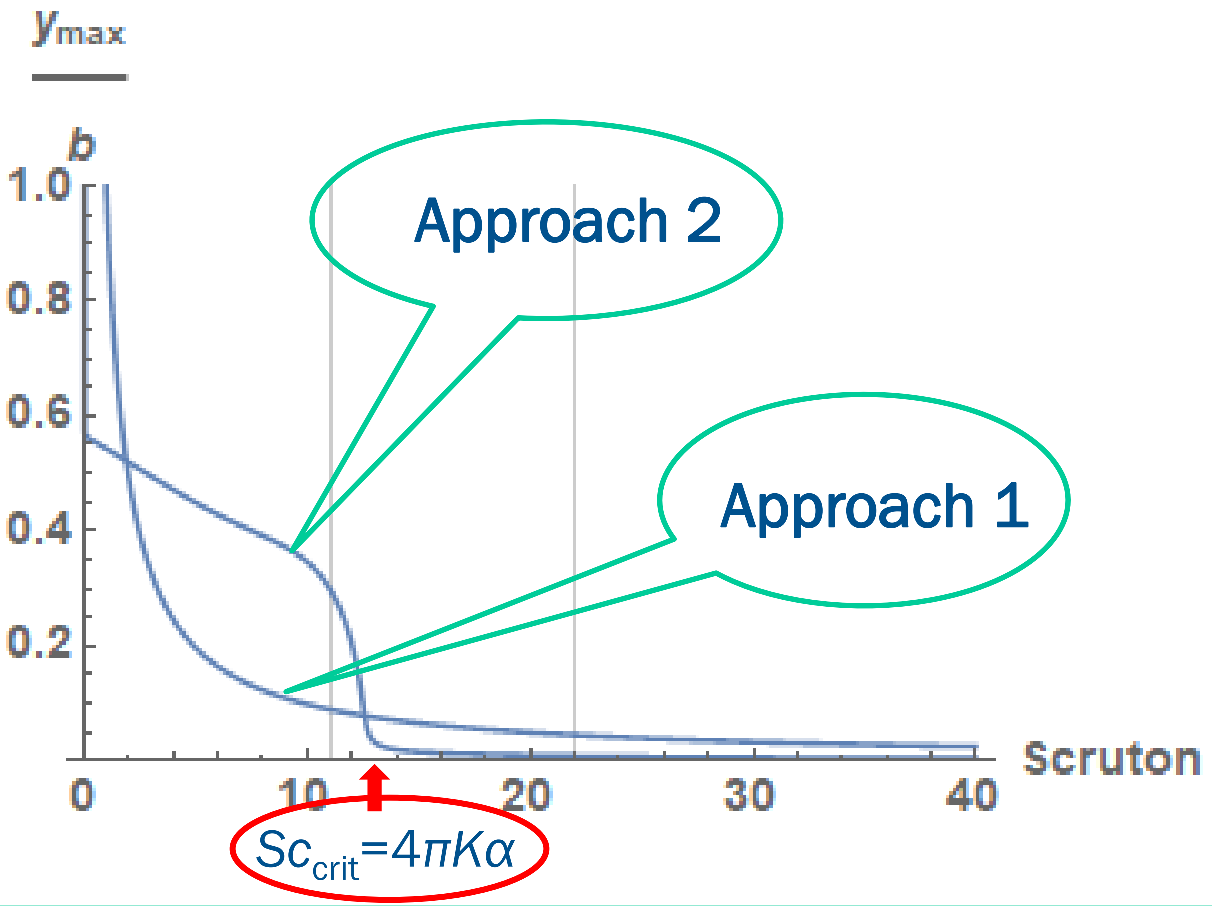
Strouhal values considered

- ❑ tower (cylinder): 0.18
- ❑ blades – root: 0.15
- ❑ blades – tip: 0.12

Oscillation amplitude of airfoils

- ❑ $\Delta C_L = 0.2$

Enhancements of VIV approach 1



Two methods available in EC

- Approach 1 simple, general but less accurate
- Approach 2 better calibrated but only applicable for the 1st bending mode of cantilever beams

Negative aerodynamic damping term

$$f(x,t) = \frac{1}{2}\rho V^2 D \; \Delta C_l \cos(\omega t) + 2\,\omega_i \,\rho\; D^2 K_a \dot{y}(x,t)(1 - G\dot{n}_i(t)^2) \;\rightarrow$$

$$Damp = 2\xi_i\omega_i\left[1 - 4\pi\frac{K_a}{Sc}\left(1 - G\dot{n}_i(t)^2\right)\right]\dot{y}_i(t)$$

where limiter $G = \frac{4}{3}\frac{1}{\omega_i^2 (y/D)_{lim}^2}$

Multi-blade configurations and tapering

$$Sc^* = Sc/(4\pi K_w K\,)$$

$$\frac{y_{max}}{D} = \frac{1}{Sc^*}\frac{1}{St^2}\frac{\Delta C_L}{4\pi}\frac{C^3}{D^3}$$

Modeling assumptions

- **Crossflow or Independence Principle (IP)**

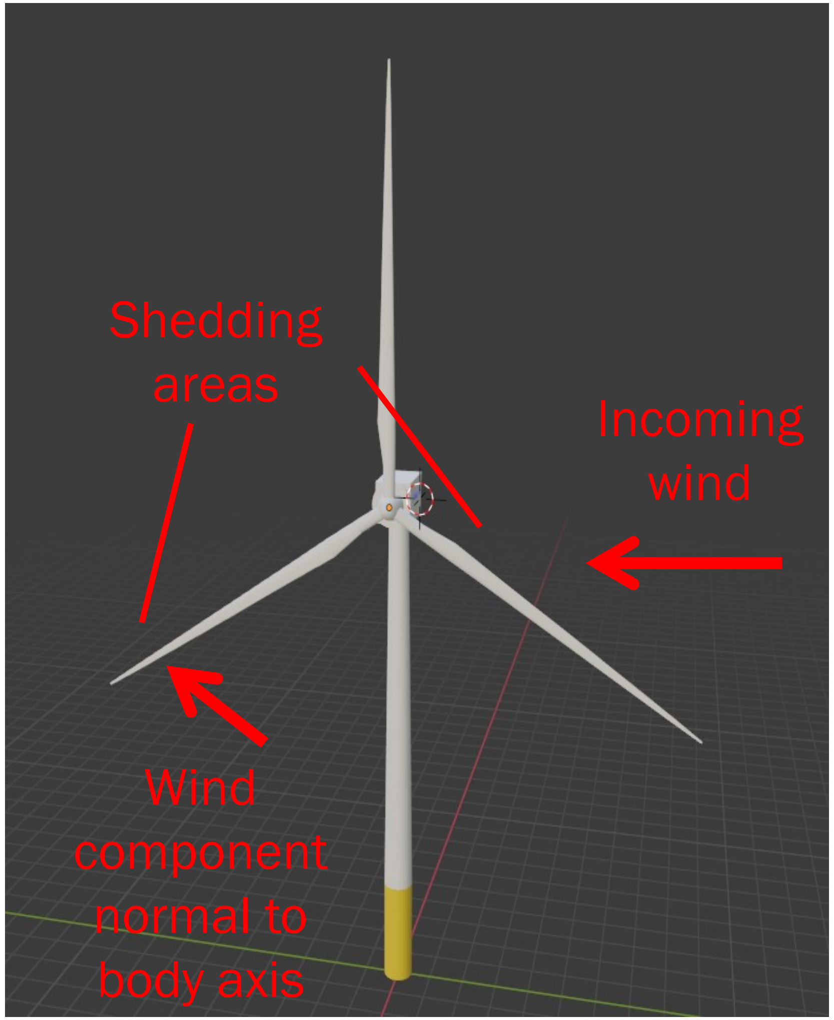
  inclined blades see the projected free stream velocity normal to the body axis.

- **Tapered blade/tower geometries**

  for tapered geometries, the reduced velocity is calculated using the mean chord/diameter of the shedding area.

- **Two blades do not shed vortices simultaneously**

  Two blades in 'Λ or V' configuration at ~90° pitch, seeing the flow from the side direction do not shed vortices at the same time, as obtained from CFD calculations.

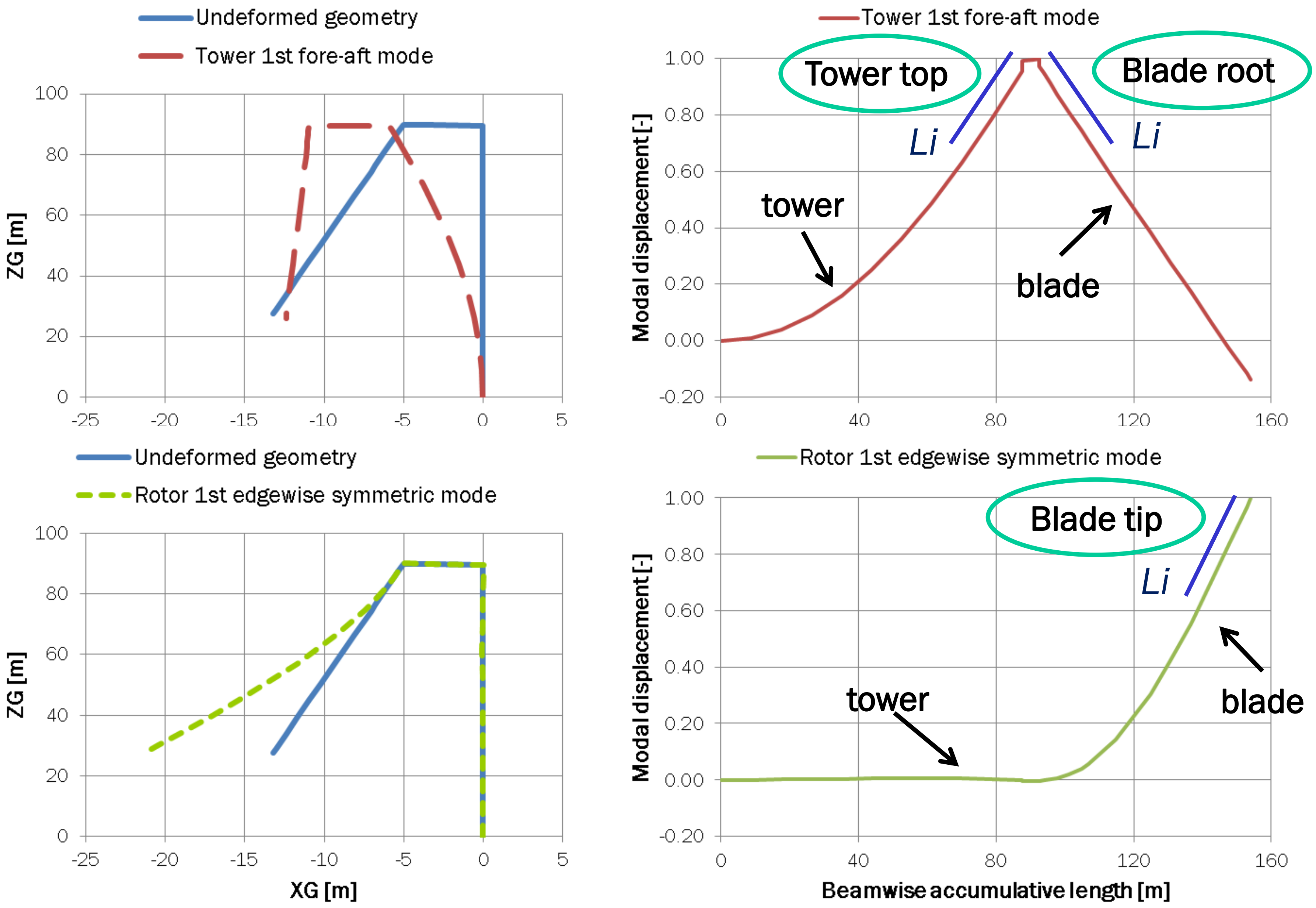


Natural frequencies of NREL5MW RWT

#	Modeshape	2 blades	1 blade
1	1st tower fore-aft	0.33	0.34
2	1st tower side-side	0.33	0.34
3	1st rotor flapwise asymmetric 1	0.69	-
4	1st rotor edgewise asymmetric 1	0.88	-
5	1st rotor flapwise symmetric	1.00	0.94
6	1st rotor edgewise symmetric	1.11	1.06
7	2nd tower fore-aft	2.79	2.78
8	2nd tower side-side	2.88	2.87
9	2nd rotor flapwise asymmetric 1	1.97	-
10	2nd rotor flapwise symmetric	2.03	2.01
11	2nd rotor edgewise asymmetric 1	2.79	-
12	2nd rotor edgewise symmetric	3.99	3.93

- 1- and 2- blades are equipped
- Rotor free, at its equilibrium position (pointing downwards), blade pitch=90°, gravity included
- Low damped modeshapes considered in VIV analysis.
- 2nd frequencies are too high to be excited within moderate-high wind speeds

Modeshapes: critical areas for VIV



Amplitude

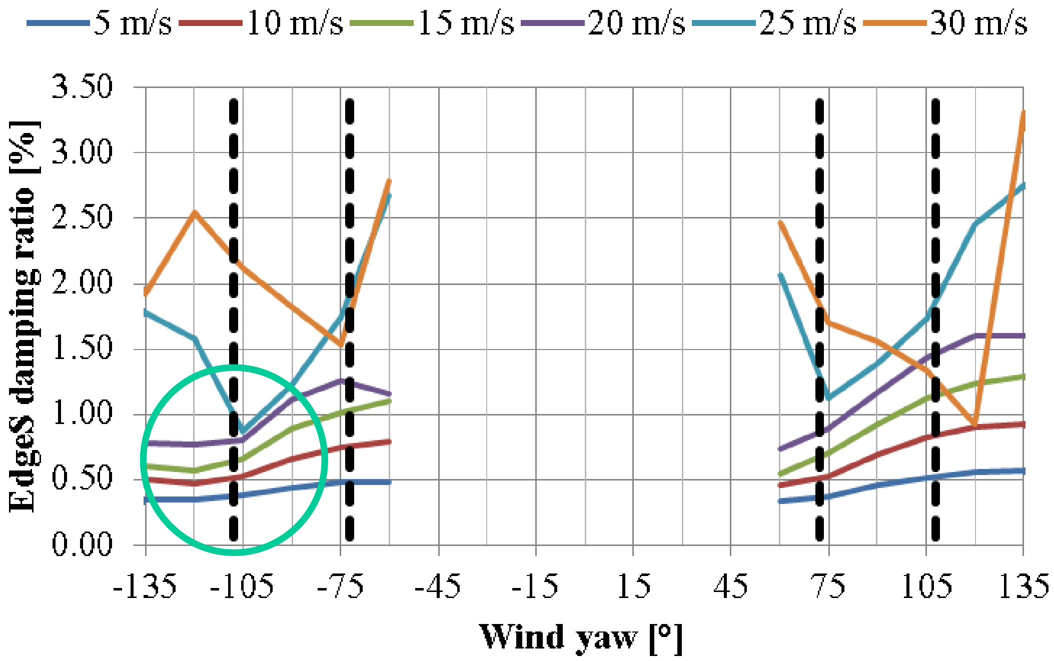
$$\frac{y_{max}}{D} = \frac{1}{Sc}\frac{1}{St^2} K_w K \Delta C_L$$

Effective correlation length

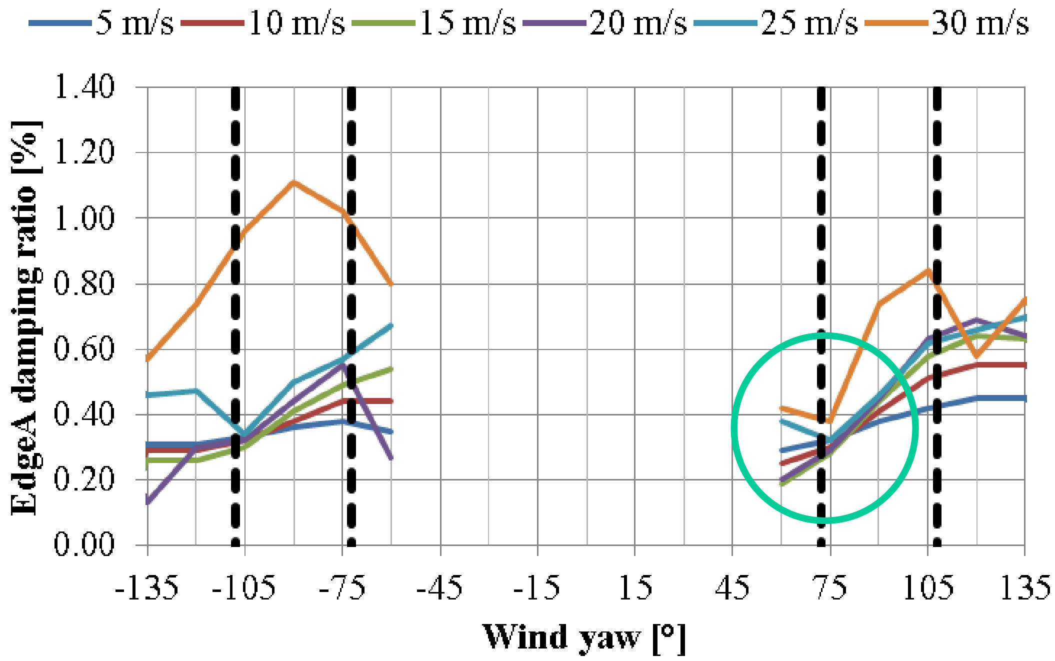
$$K_w = \frac{\int_{L_i} |\varphi_i(x)| dx}{\int_0^l |\varphi_i(x)| dx}$$

Total (Aerodynamic & Structural) Damping

Eigenvalue stability analysis with steady state aerodynamics



1st edgewise symmetric mode



1st edgewise asymmetric mode

VIV analysis results

Definition of worst VIV cases

ID	Case	Shedding	Excited mode	St	D	C	ΔC_l
[-]	[-]	[-]	[-]	[-]	[m]	[m]	[-]
1	T-T	Tower Top	1^{st} tower fore-aft	0.18	3.87	3.87	0.2
2	B-T	Blade 1 Root	1^{st} tower fore-aft	0.15	3.87	4.20	0.2
3	B-BA	Blade 2 Tip	1^{st} rotor edge asymmetric	0.12	1.40	2.40	0.2
4	B-BS	Blade 1 Tip	1^{st} rotor edge symmetric	0.12	1.40	2.40	0.2

- Damping values (critical)
  Tower : ξ=0.19%
  Blades: ξ=0.25%
- ρ_{air}=1.25 kg/m^3

Critical inflow conditions

ID	Case	1-bladded				2-bladded			
		Azimuth	V_{crit}	V_{inf}	YAW_{inf}	Azimuth	V_{crit}	V_{inf}	YAW_{inf}
[-]	[-]	[°]	[m/s]	[m/s]	[°]	[°]	[m/s]	[m/s]	[°]
1	T-T		7.3	7.3	-105		7.1	7.1	-75
2	B-T	186	9.5	9.6	-105	129	9.3	14.7	-75
3	B-BA					218	17.6	22.2	75
4	B-BS	222	21.2	28.5	-105	154	22.2	24.8	-105

VIV analysis results

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$$Sc = \frac{4\pi\xi_i\, m_{ei}}{\rho D^2}$$

$$Sc^* = Sc/(4\pi K_w K\,)$$

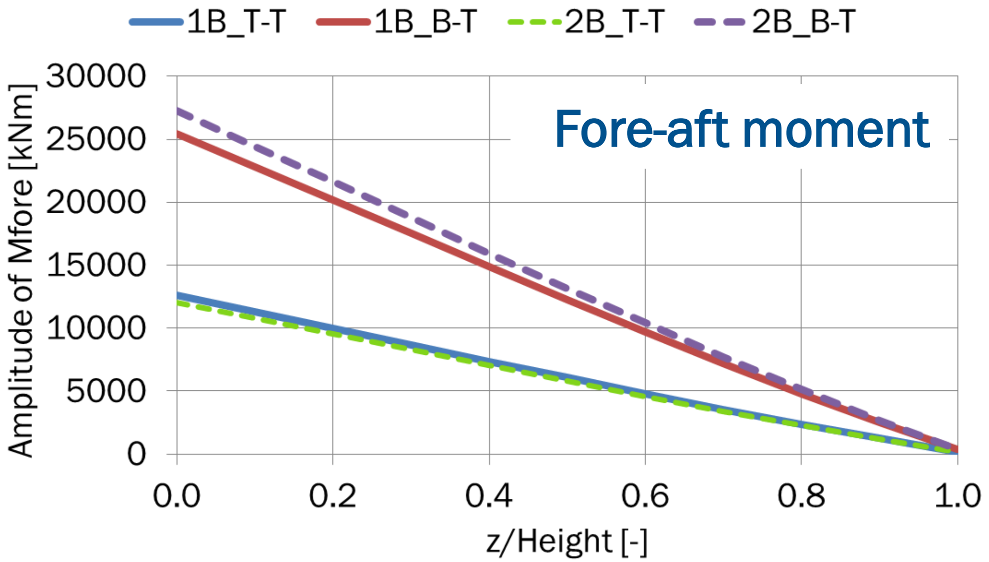
$$\frac{y_{max}}{D} = \frac{1}{Sc^*}\frac{1}{St^2}\frac{\Delta C_L}{4\pi}\frac{C^3}{D^3}$$

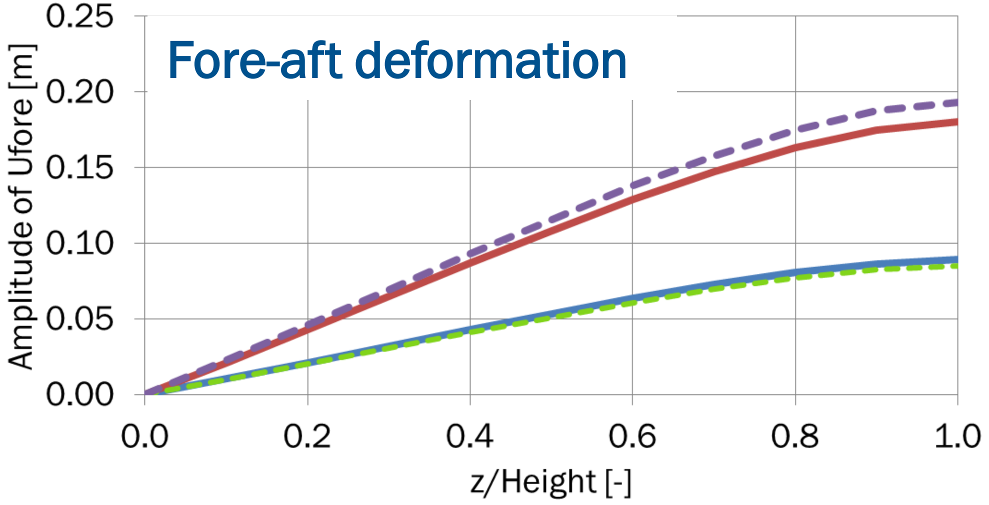
Modal parameters and maximum oscillation amplitude

			1-bladed							2-bladed						
ID	Case	L_i/C	ξ	m_e	K	Kw	Sc	Sc*	Y_{max}	ξ	m_e	K	Kw	Sc	Sc*	Y_{max}
[-]	[-]	[-]	[%]	[kg/m]	[-]	[-]	[-]	[-]	[m]	[%]	[kg/m]	[-]	[-]	[-]	[-]	[m]
1	T-T	6.0	0.18	8087	0.13	0.27	9.8	23.1	0.08	0.18	3570	0.11	0.13	4.3	24.2	0.07
2	B-T	6.0	0.18	8087	0.13	0.29	9.8	21.0	0.16	0.19	3570	0.11	0.17	4.5	19.7	0.18
3	B-BA	12.0								0.30	121	0.13	0.39	1.9	2.9	2.61
4	B-BS	12.0	1.46	105	0.14	0.60	7.9	7.4	1.06	0.87	97	0.15	0.39	4.3	5.7	1.34

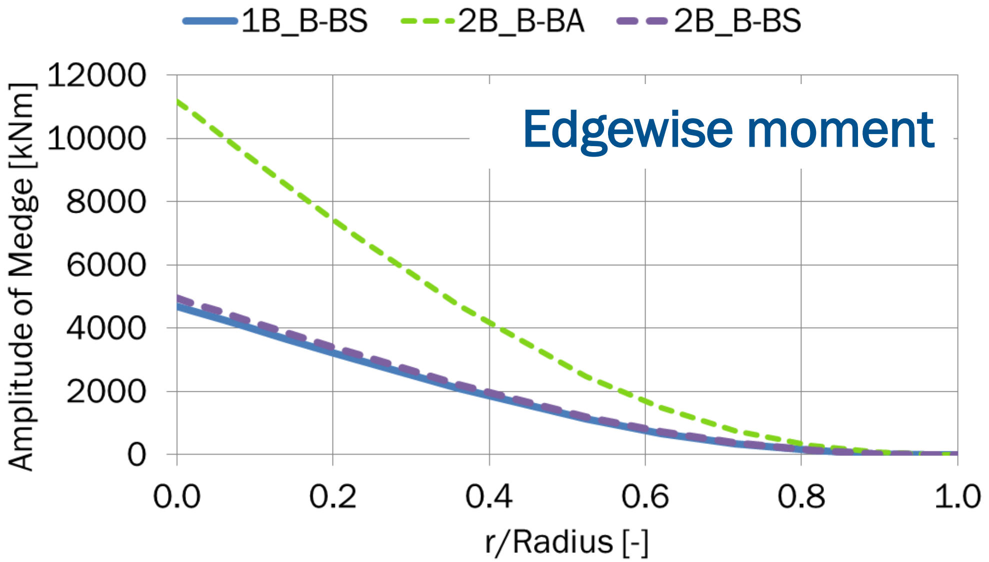
Oscillation amplitudes of moments and deformations

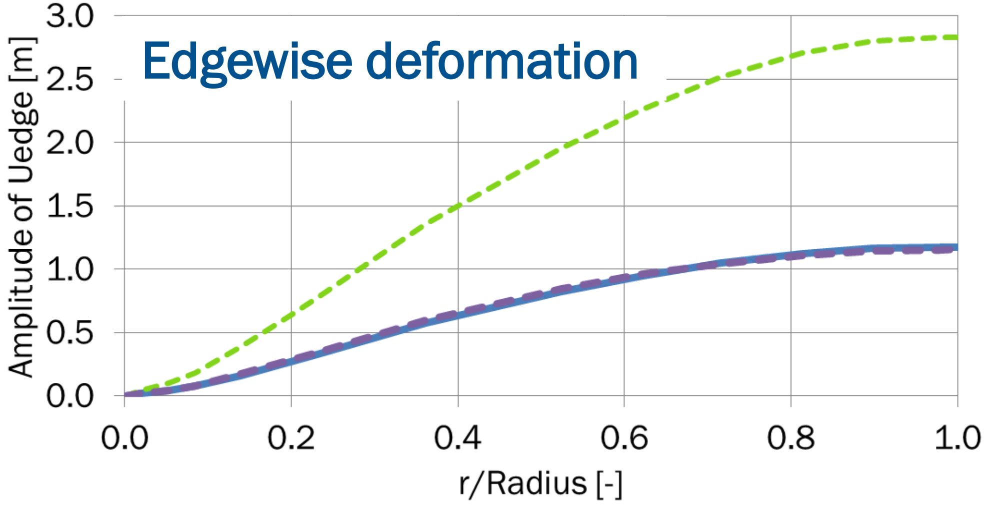
Tower (T-T and B-T)





Blades (B-BS and B-BA)





- ❑ Similar predictions for single and two-bladed setups
- ❑ T/B-T low risk

  B-BS mid risk

  B-BA high risk

Summary

- An engineering semi-empirical framework was proposed to assess VIV aero-elastic instabilities of the full (coupled) wind turbine configuration.
- It uses an extended implementation of EUROCODE “Approach 1” VIV framework for wind turbine configurations, which is incorporated in the state-of-the-art aero-elastic tool hGAST.
- It can be used during the design process to efficiently scan a wide list of critical for VIV cases and to provide the critical inflow conditions, the corresponding oscillation load and deformation amplitudes and to assess critical for VIV design parameters.
- Numerical results for single- and two-bladed configurations of the NREL 5MW RWT during assembly were presented for the worst case VIV scenarios examined.
- The VIV analysis method is trustful within the assumptions of the semi-empirical aerodynamic framework applied. It is known that the method can be quite inaccurate providing less-conservative results when instabilities do exist and more conservative when they are absent.
- To increase confidence in the results, the aerodynamic framework needs further adaptation and calibration, which is only possible through dedicated high fidelity aeroelastic analysis or experimental measurements.

Thank you