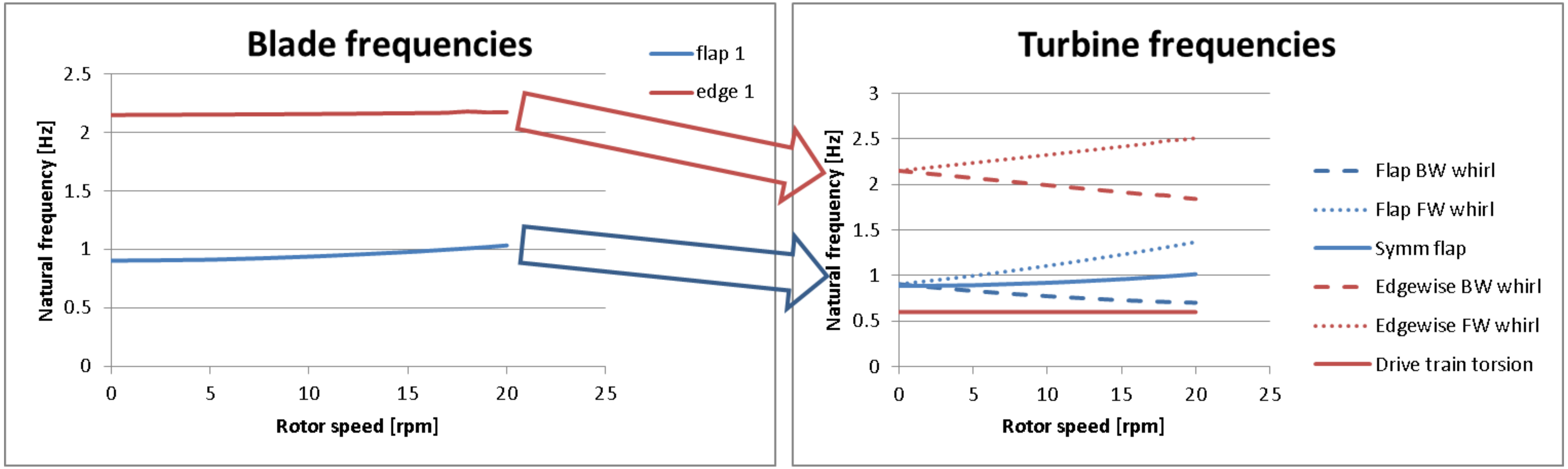
Mini-lecture Turbine Whirling Frequencies

J.G. Holierhoek

JEHO BV

Wondering why this happens?

- If we analyse natural frequencies of a wind turbine, we see this effect when comparing frequencies in the blade to those measured in a frame of reference that does not rotate (e.g. tower)



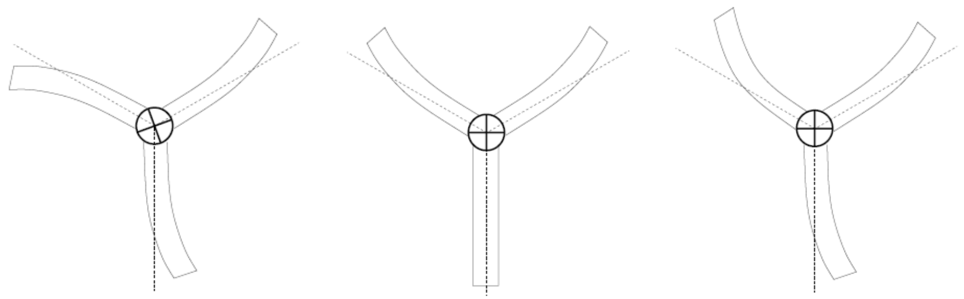
(Frequencies are representative for WT of around 2MW)

Turbine whirling frequencies

- A wind turbine **blade** will have a first flapwise mode, first edgewise mode, first torsion mode, second flapwise mode,… till infinity
- Higher modes are less relevant due to structural damping & more energy that is needed to excite a higher mode, therefore you will not have to take these modes into account
- The lower modes are very important for resonance as well as for aeroelastic stability
- **On a rotating turbine, some frequencies are measured at different values in the tower then in the blade, why?**

Turbine whirling modes

- First, what happens to the blade modes if we put three blades on one turbine?
- We find three different rotor mode shapes in for one blade mode shape:
- For example, first edgewise:



- And three similar combinations for first flapwise
- And second edgewise, and second flapwise, and…
- For two-bladed, there will be two combinations:
  - A: both same deformation (e.g. flap: both forward or edge: both clockwise)
  - B: both same but opposing deformation.
- Two-bladed is easier to depict, so let’s use 2 blades, case B

Derive equations for two-bladed

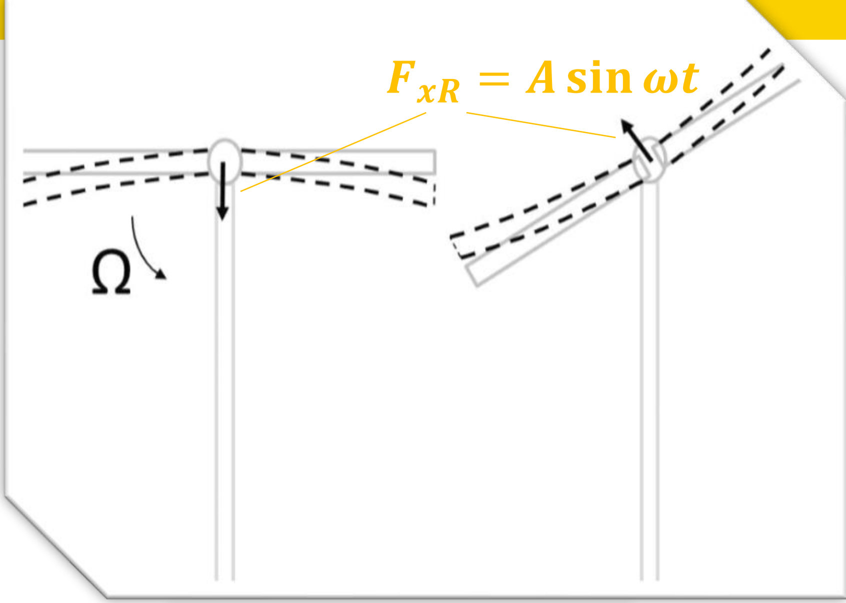
The rotor starts vibrating in the combined edgewise mode as indicated.

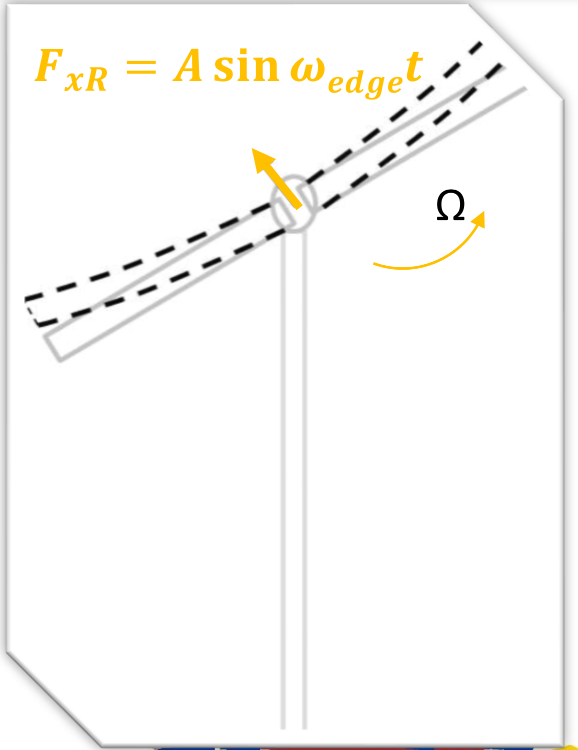
Now you can imagine the reaction force due to this vibration to be (in a rotating frame):

- $F_{xR} = A \sin \omega t$; $F_{yR} = 0$

So, the force will increase and decrease at edgewise frequency ω, but the direction rotates with the blades

Note that **stand still frame** refers only to the **reference frame**, the turbine blades are still rotating, but the frame of reference is fixed, for example in the tower directions

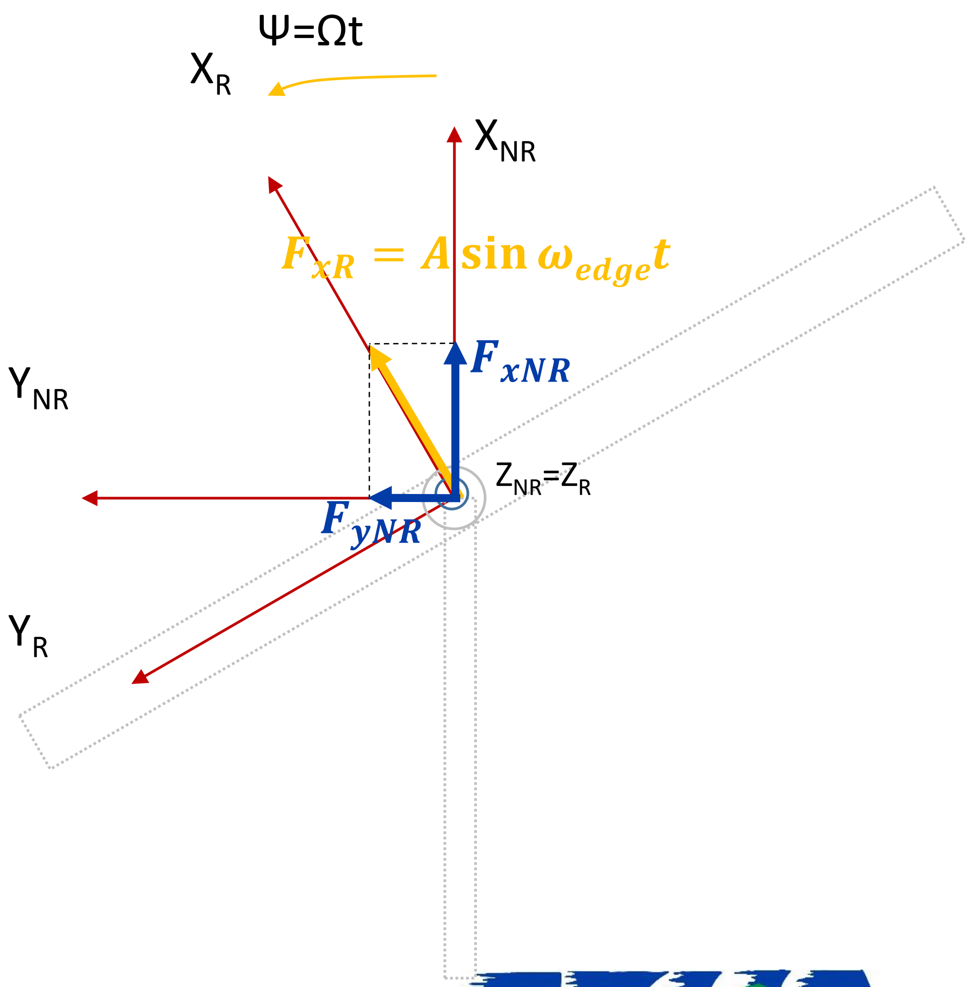




Use graph on the right and find expression for the force F_{xR} in non-rotating frame (X_{NR},Y_{NR},Z_{NR}):

This gives the following expressions in stand still frame:

$$F_{xNR} = A \sin \omega t \cos \Omega t$$
$$F_{yNR} = A \sin \omega t \sin \Omega t$$



Note that stand still frame refers only to the reference frame, the turbine blades are still rotating, but the frame of reference is fixed, for example in the tower directions

So we had:

$$F_{xNR} = A\sin\omega t\cos\Omega t$$
$$F_{yNR} = A\sin\omega t\sin\Omega t$$

Some basic mathematics:

sin(a)cos(b) = 0.5(sin(a+b) + sin(a-b))

sin(a)(sin(b) = 0.5(cos(a-b)-cos(a+b))

cos(a)cos(b)= 0.5(cos(a+b)+cos(a-b))

Using basic mathematics:

- $F_{xNR} = \frac{1}{2}A\sin((\omega-\Omega)t) + \frac{1}{2}A\sin((\omega+\Omega)t)$
- $F_{yNR} = \frac{1}{2}A\cos((\omega-\Omega)t) - \frac{1}{2}A\cos((\omega+\Omega)t)$

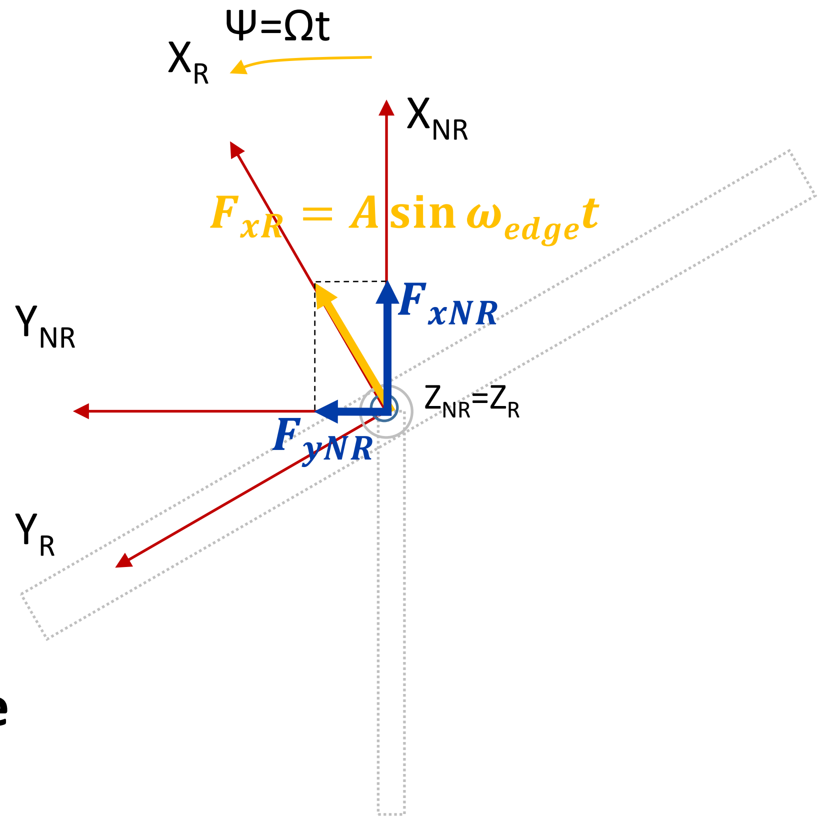
Vibrations are now at frequencies (ω-Ω) and (ω+Ω)!

This change in frequency occurs only if the **reaction force or moment is in-plane.**

If the reaction force or moment is in Z-direction (out-of-plane), it will not change from rotating to non-rotating frame.

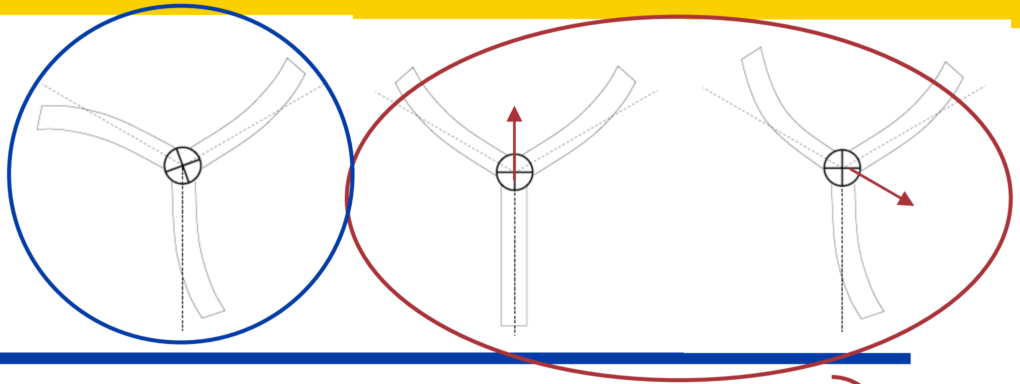
What does this mean? **If the force or moment due to the combined modes of the two or three blades are in-plane the frequency of the vibration will be measured in the tower at (ω-Ω) and (ω+Ω) and at ω in the blades…**

NOTE: a 2-bladed turbine only has one asymmetric mode, therefore it will be one mode with both frequencies in stand still frame!



Back to three-bladed turbine

Full turbine modes

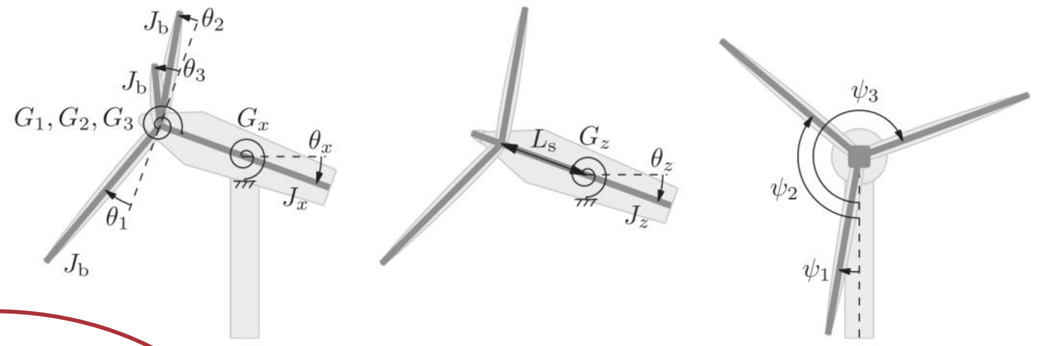


- A mode exerting a force or moment that is in the rotor plane will change in frequency when looking in the stand still frame, similar to what was illustrated for 2-bladed. For full rotating modes, one frequency will become dominant, resulting in a forward whirling ($\omega+\Omega$) or backward whirling ($\omega-\Omega$) mode.
- The collective or symmetric mode (left picture) will result in a resulting torque about the rotor shaft. Note that such a moment would not change when transforming the expression from rotating frame to stand still frame. (Similar collective flapwise results in fore/aft force)
- The combinations of blade modes are derived for stand still turbine. On a rotating turbine the full rotor modes will look different…..

* There is also some yaw hinge present, but the discussion is about the blades only

Isotropic turbine, simple model

P.F. Skjoldan, M.H. Hansen. On the similarity of the Coleman and Lyapunov-Floquet transformations for modal analysis of bladed rotor structures. *Journal of Sound and Vibration*, 327:424–439, 2009
https://orbit.dtu.dk/files/5509069/ris-phd-66.pdf



Simple turbine model, 5 DOFs: 3 flapping blades, tilt and yaw hinges.
Using **Coleman transformation**, 3 flap DOFs change to rotor symmetric, rotor tilt and rotor yaw DOFs. These three concern combinations of the three blades, not the tilt and yaw hinge in the model. With these new coordinates, the modes can be derived and are illustrated to the right.
(a) BW whirling mode, graph illustrates that at rotor speed = 0, only yaw blade mode is present*, but for other rpms, the mode changes to a pure BW whirling mode

$$A_{0,k} = \frac{1}{3}\sum_{i=1}^{3}\theta_i\,;\,A_{a1,k} = \frac{2}{3}\sum_{i=1}^{3}\cos\psi_i\,\theta_i\,;\,A_{b1,k} = \frac{2}{3}\sum_{i=1}^{3}\sin\psi_i\,\theta_i$$

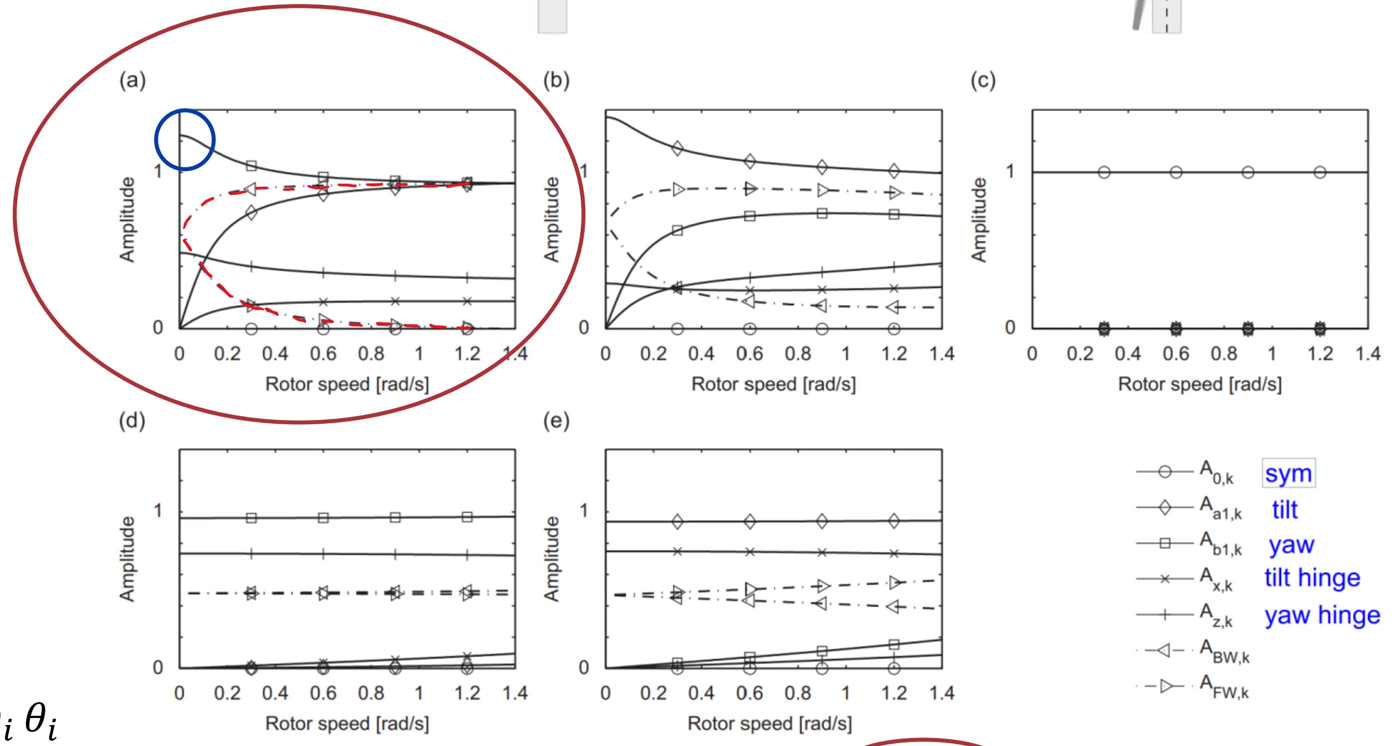


Fig. 2. Normalized modal amplitudes and whirling amplitudes versus rotor speed Ω. (a) First BW mode; (b) first FW mode; (c) symmetric mode; (d) second yaw mode; and (e) second tilt mode.

Isotropic turbine, simple model BW whirling

Lyapunov–Floquet transformation approach

P.F. Skjoldan, M.H. Hansen. On the similarity of the Coleman and Lyapunov-Floquet transformations for modal analysis of bladed rotor structures. *Journal of Sound and Vibration*, 327:424–439, 2009 https://orbit.dtu.dk/files/5509069/ris-phd-66.pdf

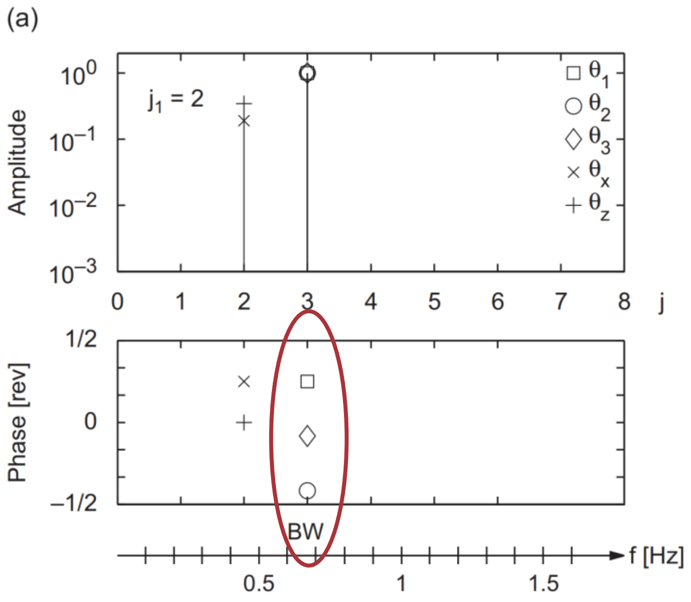
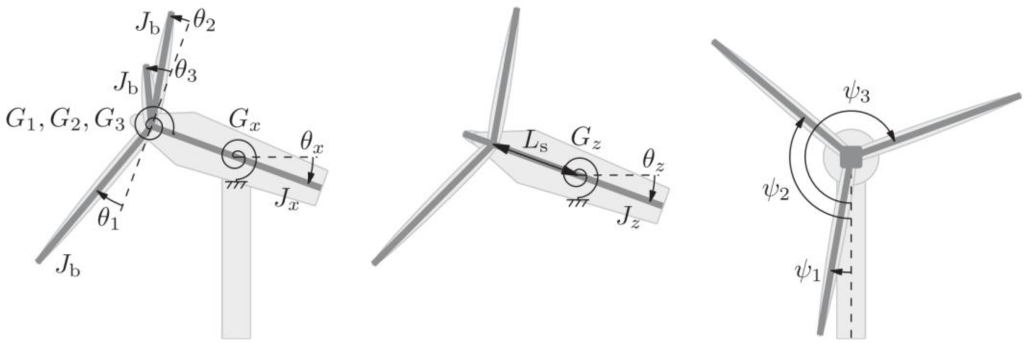


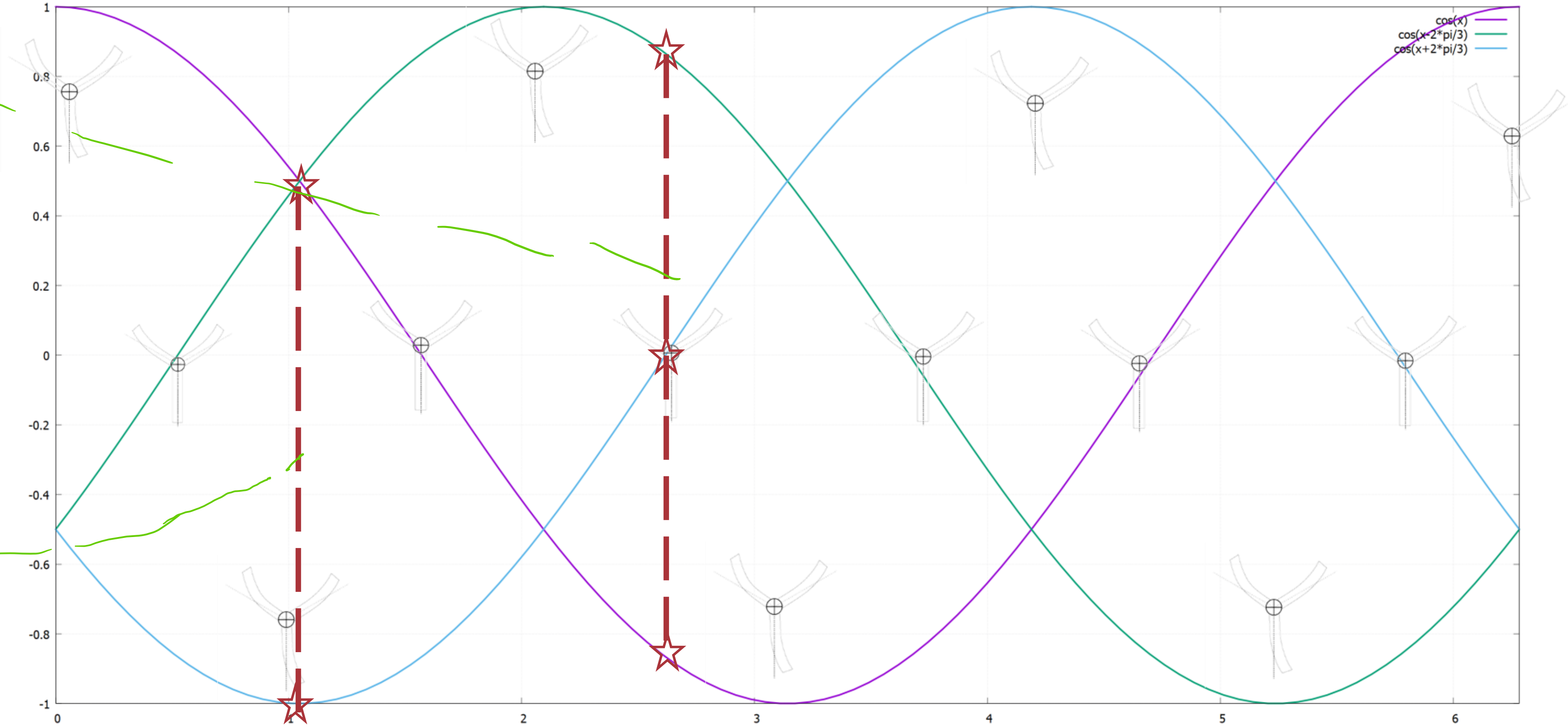
Fig. 4. Amplitudes (log. scale) and phases of harmonic components $\mathcal{U}_{p,j,ik}$ (36) in the principal periodic mode shape for the isotropic rotor at $\Omega = 1.4$ rad/s. The bottom scale shows the frequencies in the response measured in the inertial system as $(j - j_k)\Omega + \omega_k = j\Omega + \omega_{p,k}$ using (35). (a) First BW mode



At rated rotor speed, this simple model results in a clear BW whirling flapwise mode, each blade deformation has the same amplitude, but a different phase. Similar rotor mode can be expected for edgewise mode

Blade vibrations whirl

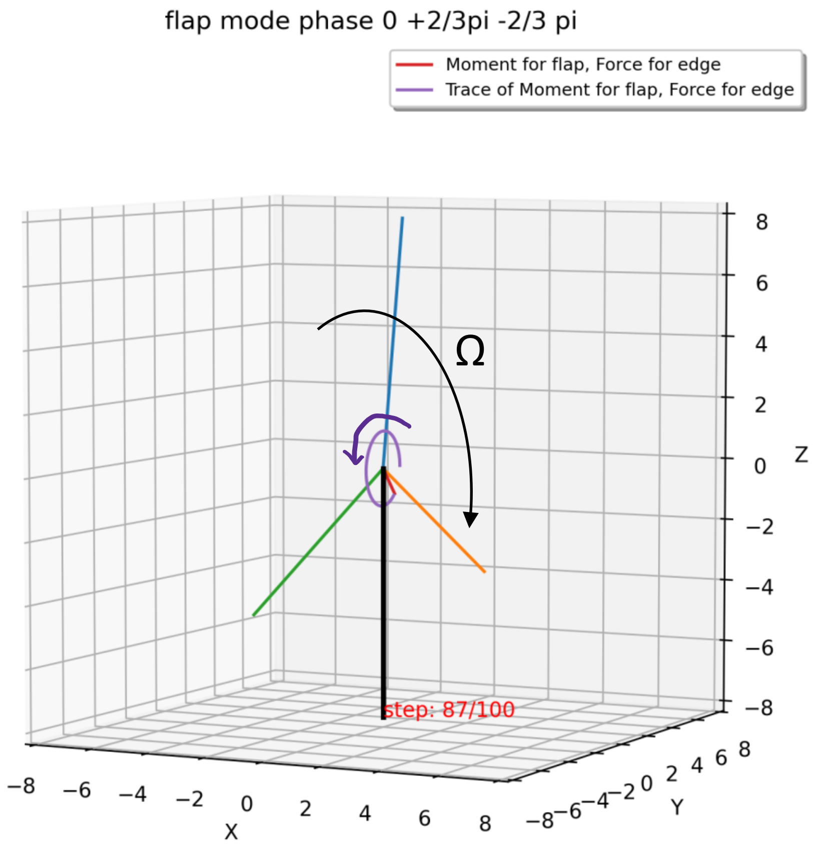
- Note that the stand still modes that were first found are not so different from the final mode on rotating turbine with phase differences:
- When one blade is at 0, the other two have identical deformations but in the opposite direction
- When one blade is at max/min deformation, the other two are at -0.5* that deformation

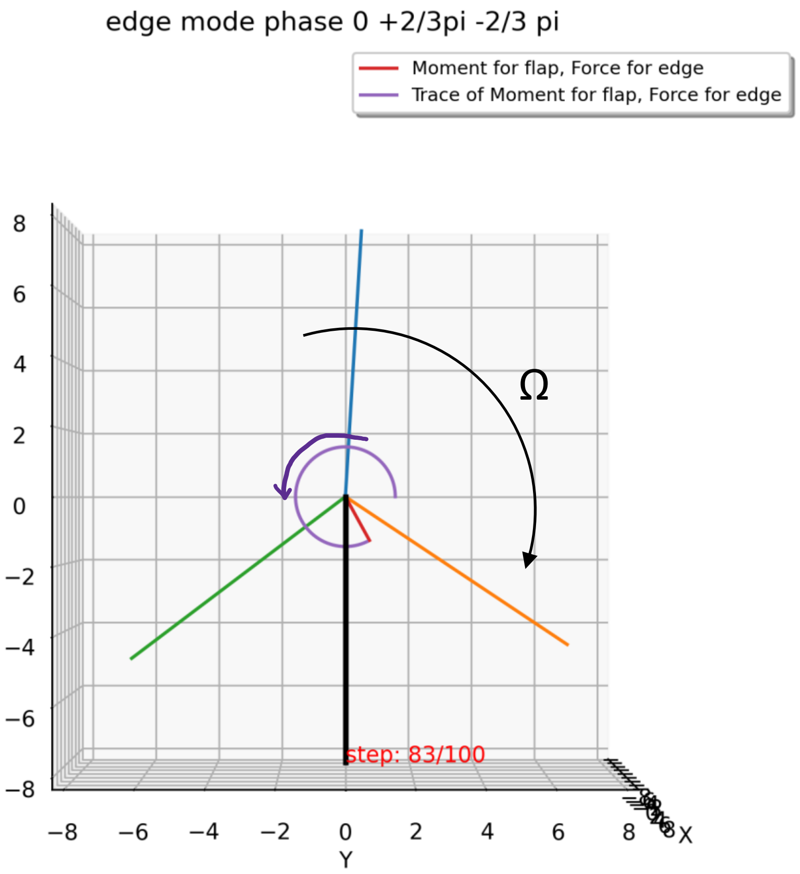


BW whirling modes isotropic model

Illustrating the force/moment at the tower top when blades vibrate in flapwise (left) or edgewise (right) mode phase as indicated in the picture of the previous slide.

Moment/force shows circle in direction opposite to rotor rotation (NOTE THAT ROTOR ROTATION ITSELF IS NOT USED, THIS IS THE FORCE CHANGE DURING 1 MODE VIBRATION)





BW whirling modes isotropic model

- The graphs are only illustrating moment/force due to blade bending deformations, not the interaction with tilting or yawing degrees of freedom (they were included in the calculated mode in the referenced paper).
- The forces form a complete circle **during one edgewise vibration**
- The rotor rotation will not change the shape of the circle but will only increase (for BW whirl) or decrease (in case of FW whirl) the time needed for the full circle to be completed.
- Therefore, for this BW whirl mode, the tower will sense only the (ω-Ω) frequency.
- This is true for BW whirl in this very simple and isotropic model, in more realistic (anisotropic) models the mode will become a combination of frequencies, with one dominating frequency.

Summary:

- Edgewise whirling (asymmetric) modes: resulting forces are in-plane.
- So these edgewise modes have different frequency in non-rotating reference frame than in rotating frame
- Flapwise whirling modes: resulting moments are in-plane (yawing / tilting => vector of moment will be in-plane!).
- So flapwise asymmetric modes also have different frequency in non-rotating reference frame than in rotating frame.
- Note that turbine is rotating in all situations, we only define different reference frames (e.g. measuring at blade root versus in tower)
- On a rotating turbine for higher rotor speeds the modes change from the stand still modes to modes with identical amplitudes for each blade but different phases resulting in FW or BW whirl.

www.jeho.nl About Wind Turbine Aeroelasticity:

More reading material:

Home www.jeho.nl

Leaflets Tools CONSULTANCY SERVICES Quiz About Wind Turbine Aeroelasticity Training Options Contact

Reading material

Open access

Includes the paper from slides 11,12

- **Explanation of wind turbine modes**
  - Modal dynamics of structures with bladed isotropic rotors and its complexity for two-bladed rotors Morten Hansen Wind Energy Science 1-2016
  - Modal properties and stability of bend–twist coupled wind turbine blades Alexander Stäblein et al. Wind Energy Science 2-2017
  - PhD thesis Aeroelastic modal dynamics of wind turbines including anisotropic effects, Peter Fisker Skjoldan, 2011
  - Multiblade Coordinate Transformation and Its Application to Wind Turbine Analysis G. Bir, 2008 – NREL
- **General introduction to WT aeroelasticity**
  - PhD thesis Aeroelasticity of Large Wind Turbines Jessica Holierhoek, 2008
  - A chapter Aeroelastic Stability Models in the book Handbook of Wind Energy Aerodynamics (not open access).
- **Instabilities**
  - Aeroelastic Instabilities of Large Offshore and Onshore Wind Turbines, G. Bir and J. Jonkman 2007 – NREL
  - **Idling instabilities:**
    - Aeroelastic stability of idling wind turbines Kai Wang et al. Wind Energy Science 2-2017
    - Stability analysis of parked wind turbine blades using a vortex model Vasilis Riziotis et al.
  - **Overspeed instabilities (classical flutter or edgewise):**
    - Field validation of the Stability Limit of a Multi MW turbine Bjarne S. Kallesøe, The science of making torque from wind 2016
    - Flutter behavior of highly flexible blades for two- and three-bladed wind turbines Mayank Chetan, Shulong Yao, and D. Todd Griffith Wind Energy Science 7-2022
- **Journals**
  - Wind Energy Science: a very good open access journal
  - Wind Energy – Wiley: a very good journal with more and more open access articles being published

Did you find this interesting?

Get to know why the fact that whirling edgewise modes do not interact with generator is so important and much much more during our wind turbine aeroelasticity course. Info: www.jeho.nl

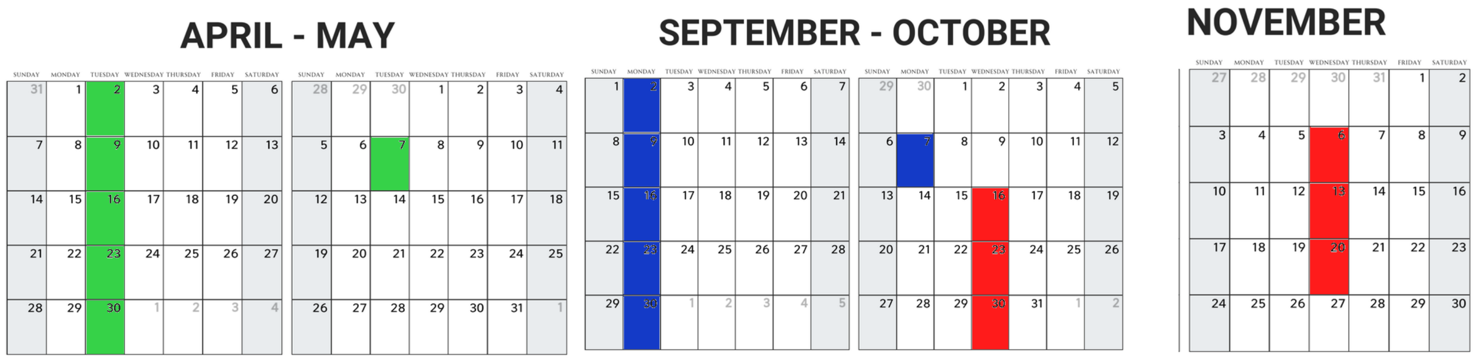
And follow us on LinkedIn to keep updated on our mini lectures and more!

WTAC_2024_11

Schedule 2024 open courses ON-LINE

Online live web training sessions **wind turbine aeroelasticity course**. Small groups of participants.

Six mornings, each week a four-hour training session.



April/May 2024: Tuesdays
2/9/16/23/30 April & 7 May
09:00-13:00 CEST (3-7 pm Bejing Time)

September/October 2024: Mondays
2/9/16/23/30 September & 7 October
09:00-13:00 CEST (3-7 pm Bejing Time)

October/November 2024: Wednesday
16/23/30 October & 6/13/20 November
16 & 23 October 09:00-13:00 CEST (3-7 pm Bejing Time)
30 October and later lessons 09:00 – 13:00 CET (4-8 pm Bejing Time)

Interested in attending?
Contact us: workshop@jeho.nl