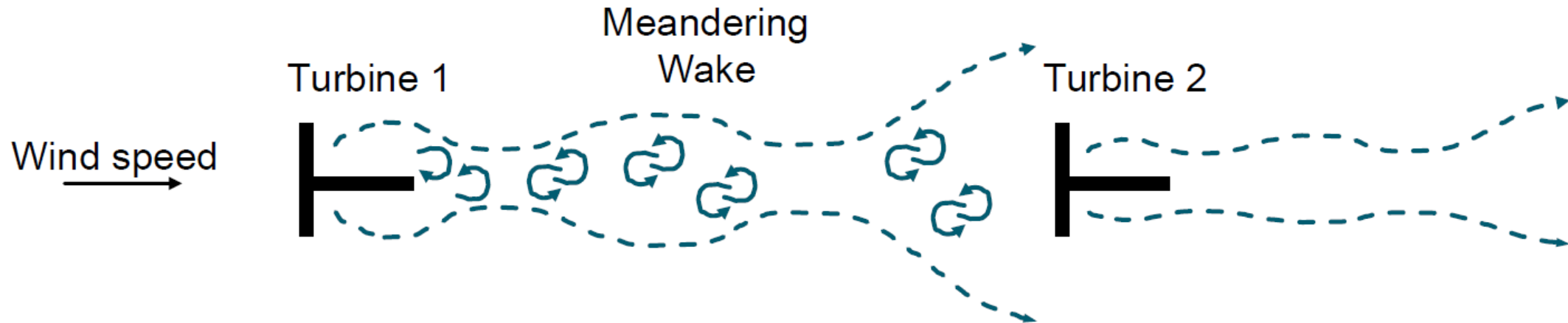


Dynamic analysis of the wake simulation data

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Simulation and data description

- 2 NREL 5MW wind turbines in a row (Turbine 1 is upstream, Turbine 2 is in the wake)

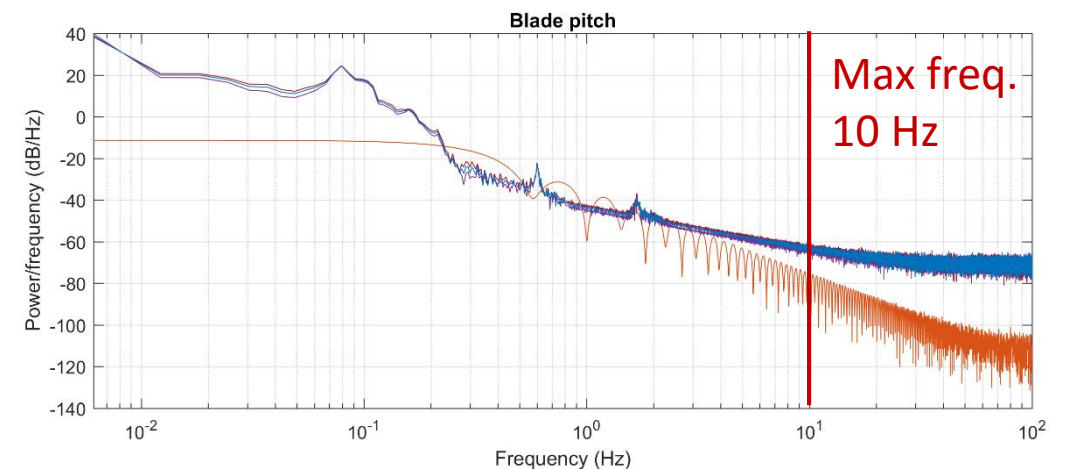
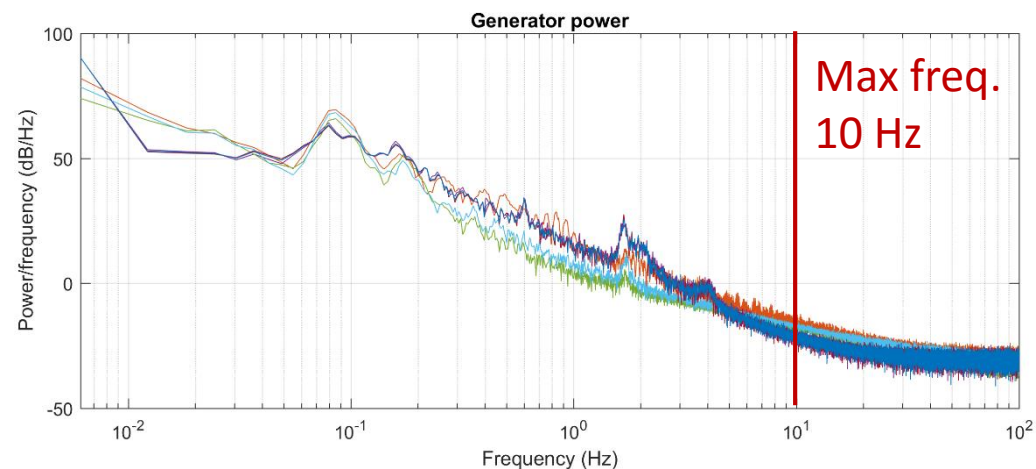
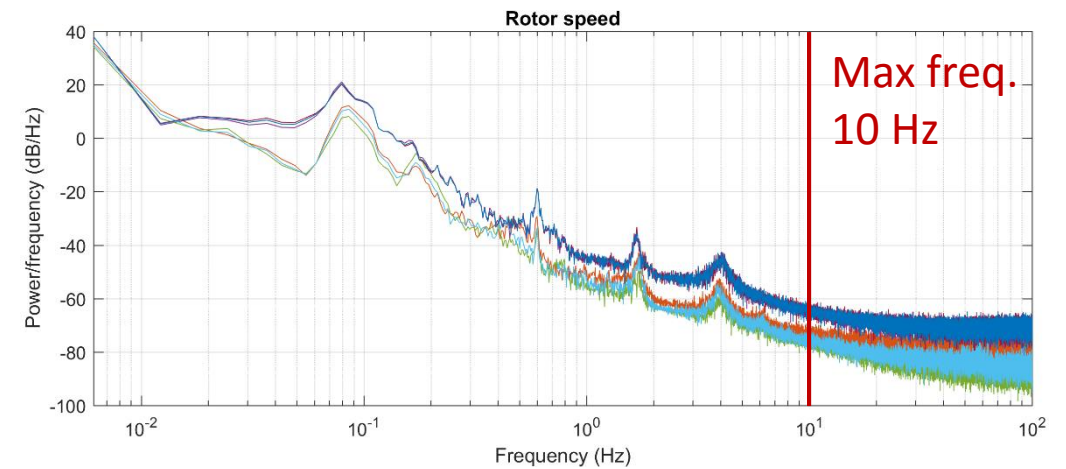
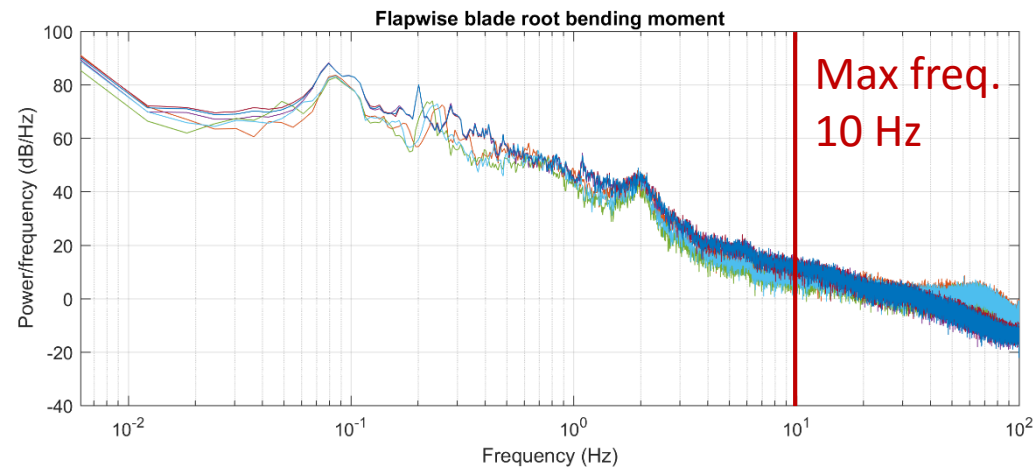


Simulation and data description

- 4 Setups:
 1. Mean wind speed = 8m/s, Turbulence intensity = 18%, distance between turbines 2D
 2. Mean wind speed = 8m/s, Turbulence intensity = 18%, distance between turbines 7D
 3. Mean wind speed = 18m/s, Turbulence intensity = 10%, distance between turbines 2D
 4. Mean wind speed = 18m/s, Turbulence intensity = 10%, distance between turbines 7D
- The setup above includes the following combination of scenarios:
 - Partial load operation @8m/s
 - Full load operation @18m/s
 - Very Closely spaced turbines @2D
 - Far spaced turbines @7D
- DWM-FAST simulated time series data:
 - Flapwise root bending moment
 - Blade pitch
 - Wind speed
 - Rotor speed
 - Generator power

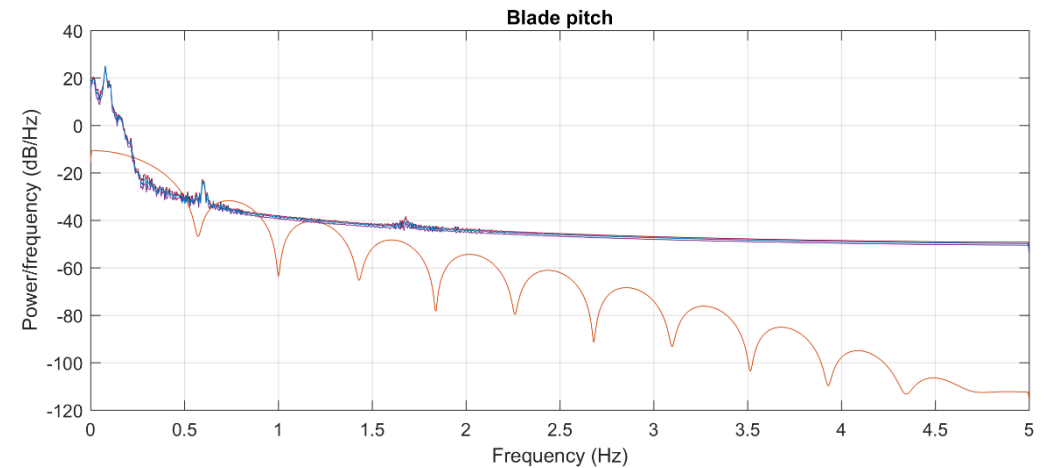
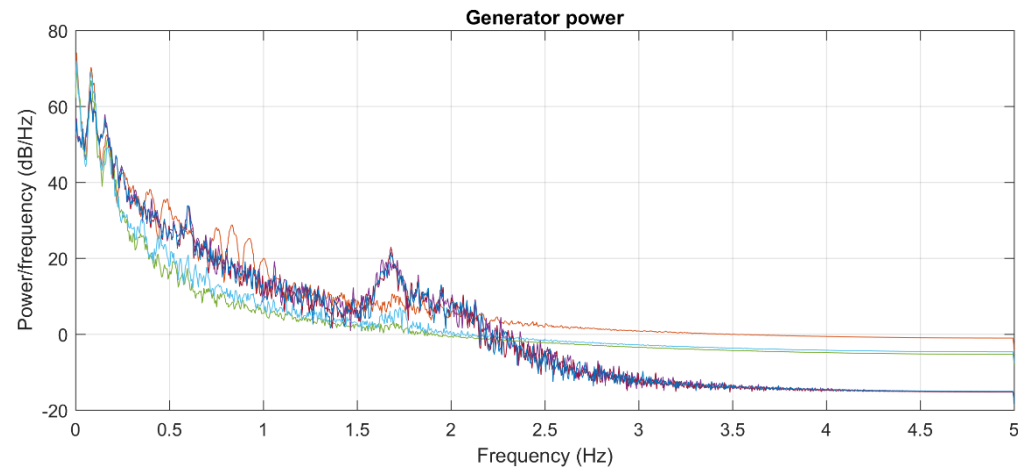
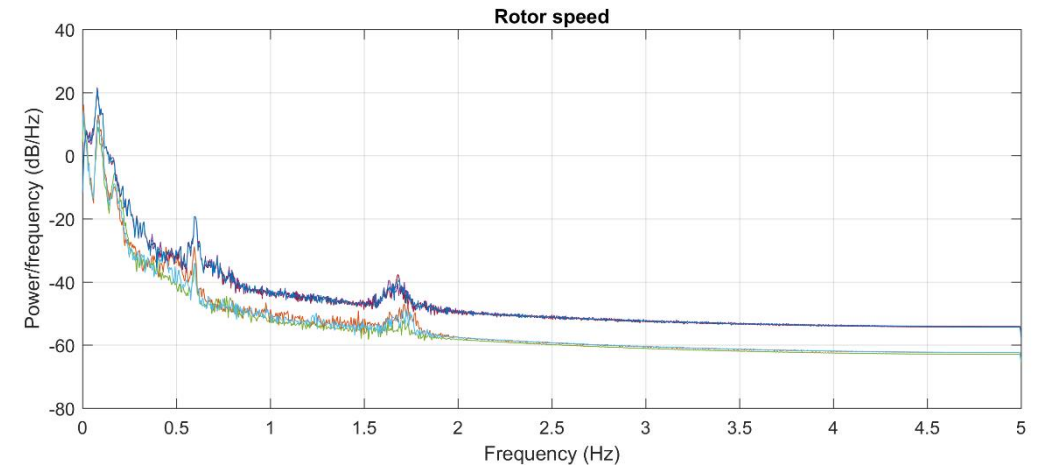
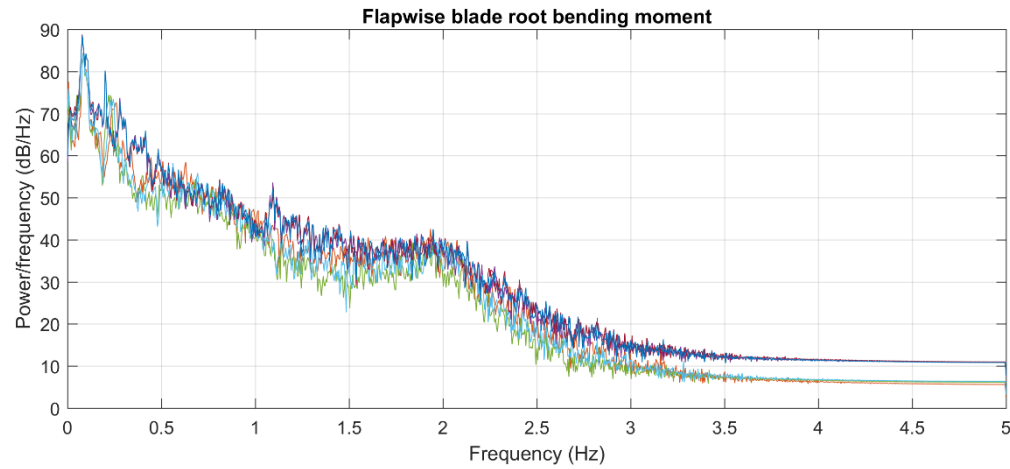
Simulation and data description

- Properties: Sampling frequency: 200 Hz; Simulation period: 600 s = 10 min; No. Samples: 120k
- Welch PSD estimate: Hamming window; window size: 2^{11} samples; overlap: 2^{10} samples



Simulation and data description

- Pre-processing: Detrending; downsampling at 10 Hz
- Welch PSD estimate: Hamming window; window size: 2^{15} samples; overlap: 2^{14} samples



PSD analysis

Table 9-1. Full-System Natural Frequencies in Hertz

Mode	Description	FAST	ADAMS
1	1st Tower Fore-Aft	0.3240	0.3195
2	1st Tower Side-to-Side	0.3120	0.3164
3	1st Drivetrain Torsion	0.6205	0.6094
4	1st Blade Asymmetric Flapwise Yaw	0.6664	0.6296
5	1st Blade Asymmetric Flapwise Pitch	0.6675	0.6686
6	1st Blade Collective Flap	0.6993	0.7019
7	1st Blade Asymmetric Edgewise Pitch	1.0793	1.0740
8	1st Blade Asymmetric Edgewise Yaw	1.0898	1.0877
9	2nd Blade Asymmetric Flapwise Yaw	1.9337	1.6507
10	2nd Blade Asymmetric Flapwise Pitch	1.9223	1.8558
11	2nd Blade Collective Flap	2.0205	1.9601
12	2nd Tower Fore-Aft	2.9003	2.8590
13	2nd Tower Side-to-Side	2.9361	2.9408

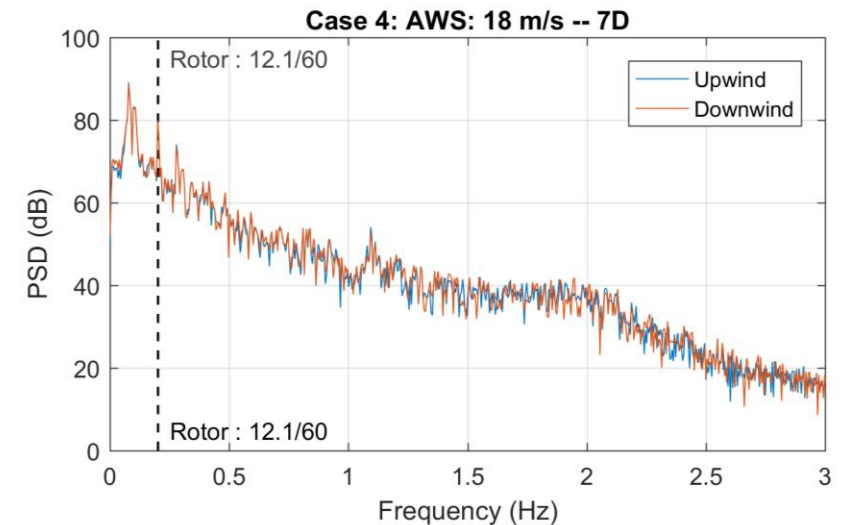
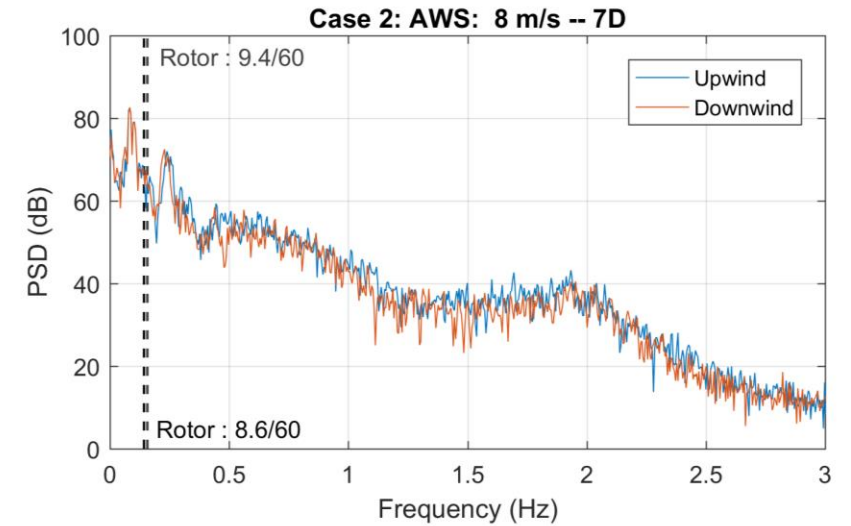
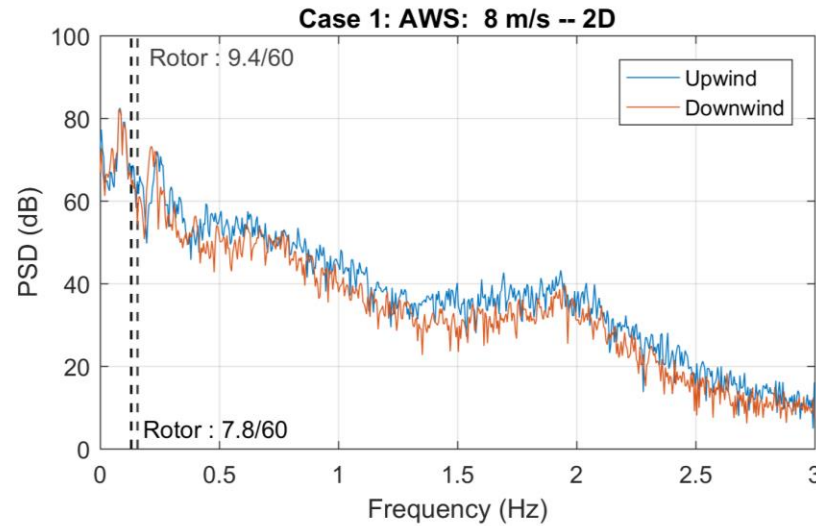
PSD analysis

Welch PSD estimate:

- Hamming window
- Window size: 2^{11} samples
- Overlap: 2^{10} samples

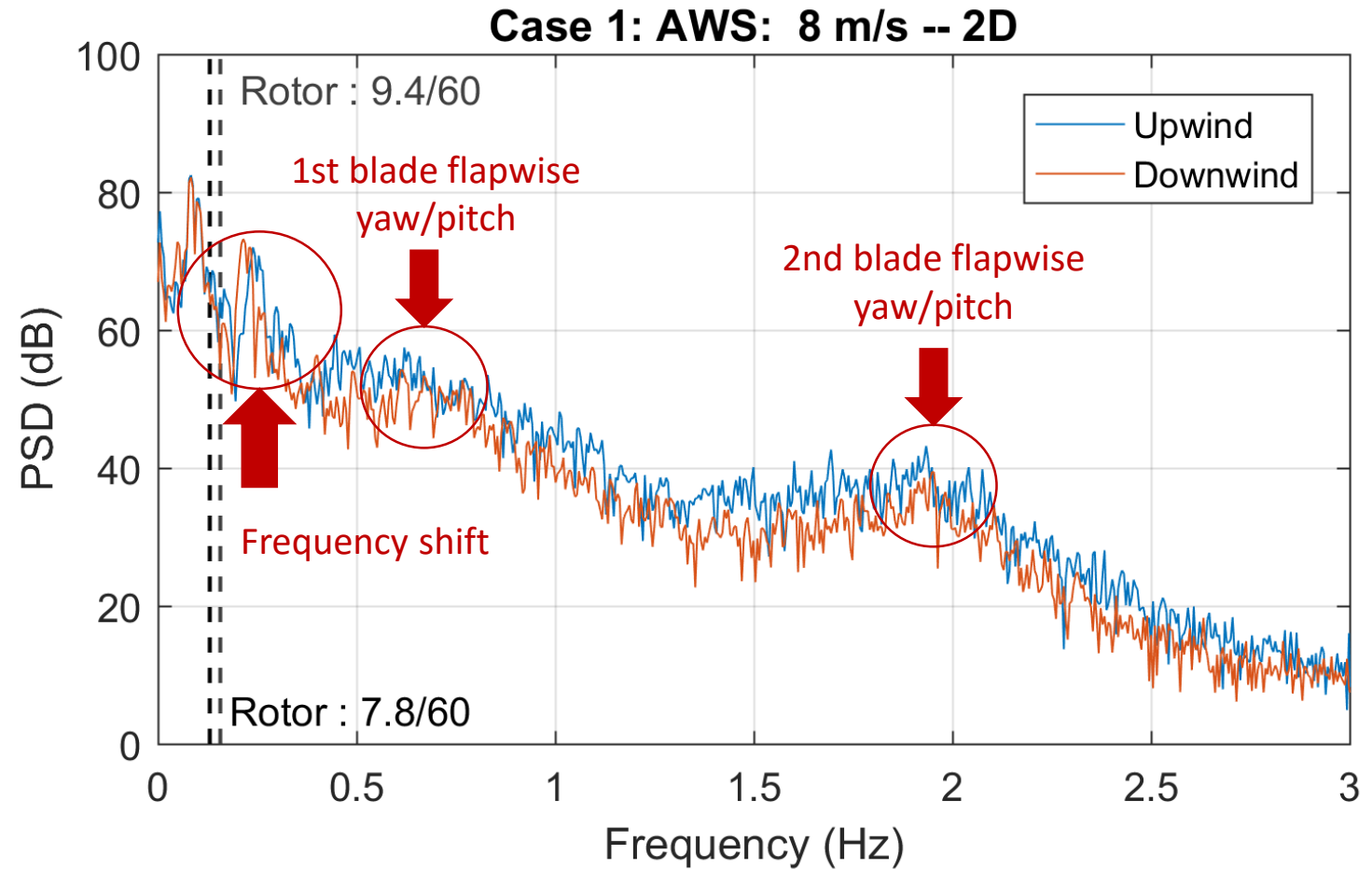
PSDs show differences for low wind speed case

Differences not so evident on high wind speed case



PSD analysis

- Highly damped 1st and 2nd blade flapwise modes
- Large underdamped low-frequency modes
 - Apparently correspond to 0.5P and 1.5P
- One of the underdamped modes shows an evident frequency shift in upwind/downwind cases
 - This may be associated to the change in wind speed
- Overall power in the blade moment is larger in the upwind case

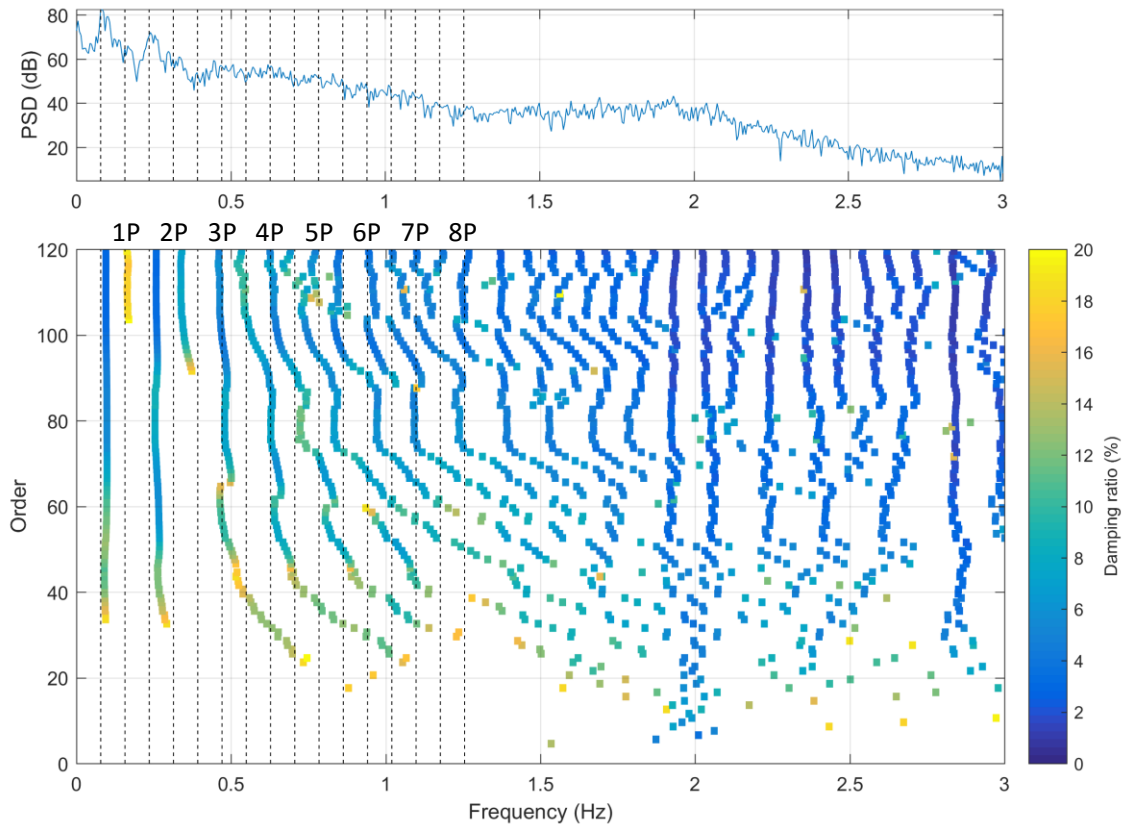


Parametric analysis – AR modeling

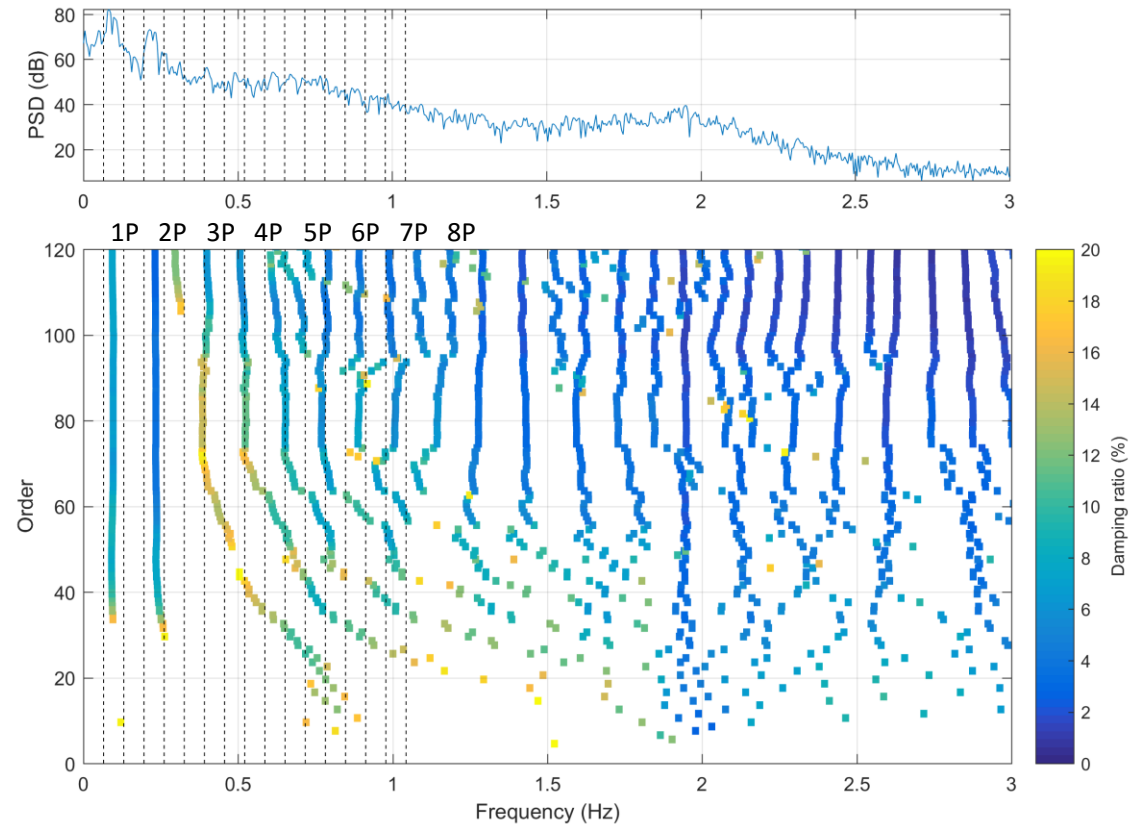
- Blade root bending moment identified via AR models
- AR model order up to 120 delays

Parametric analysis – AR modeling

Upwind turbine – 8 m/s – 2D



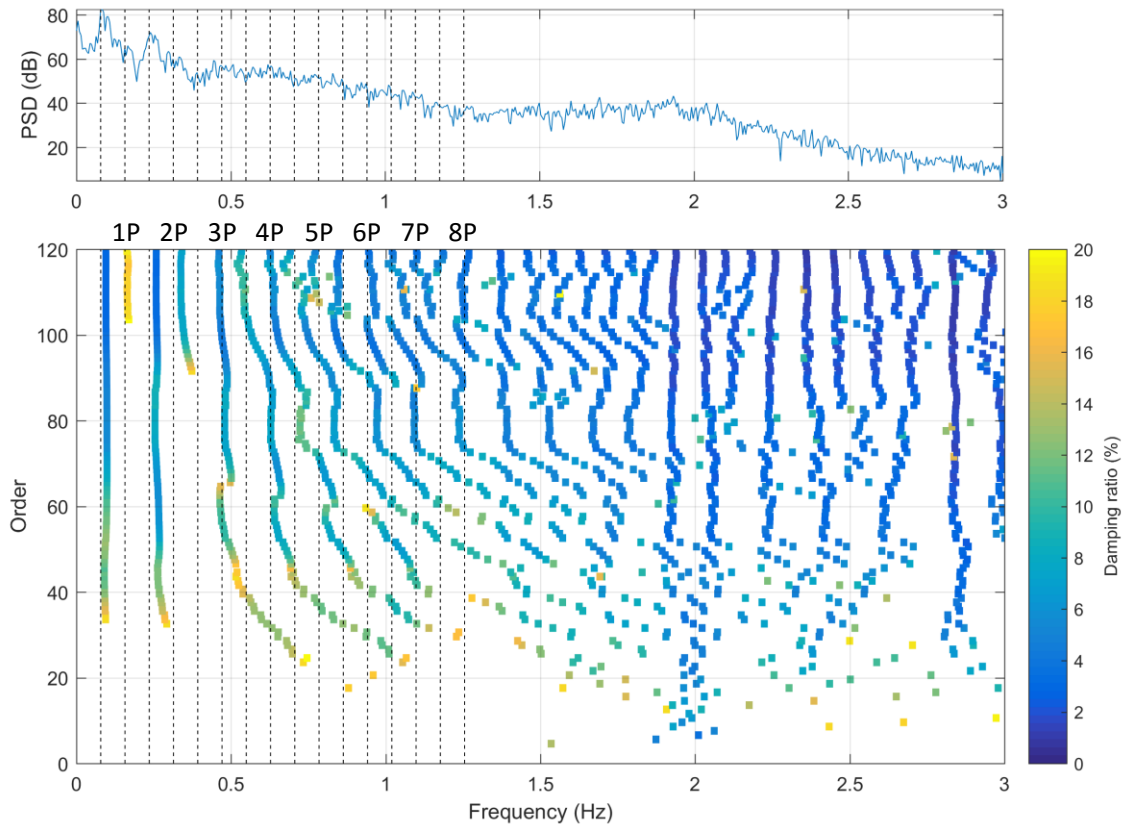
Downwind turbine – 8 m/s – 2D



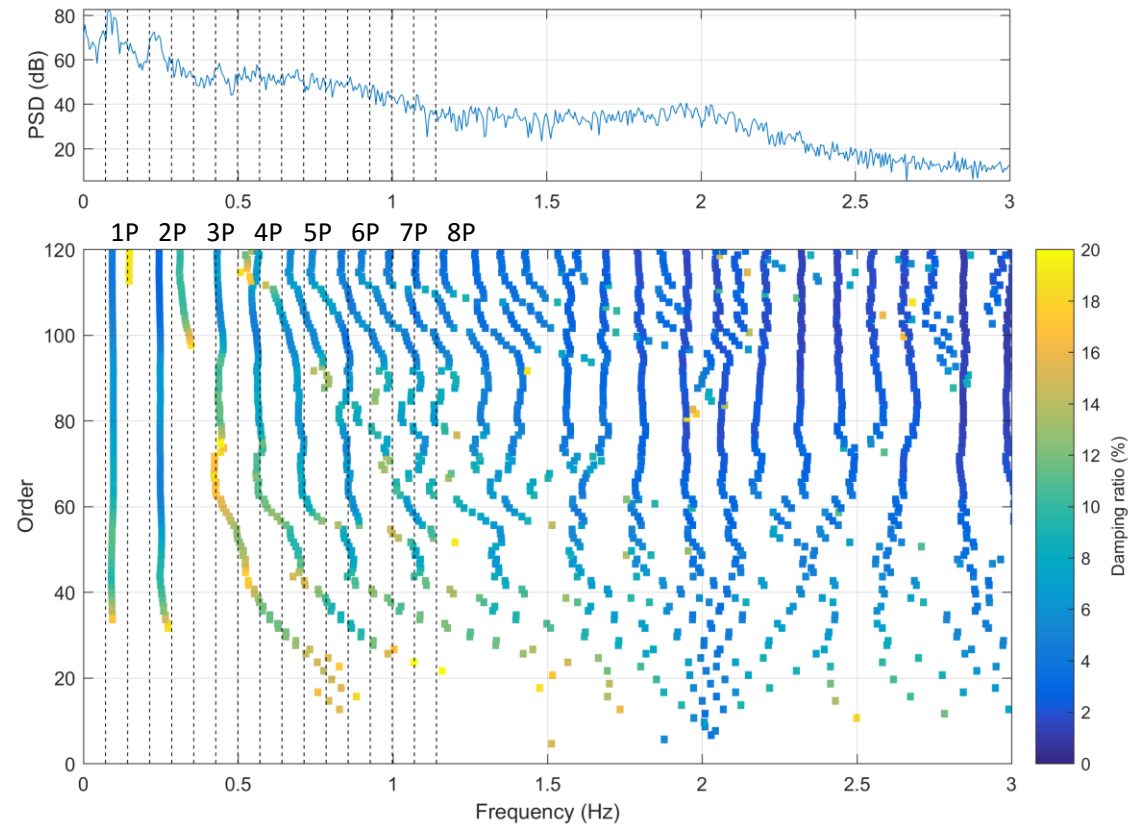
Modes with damping ratio under 20% are displayed. Vertical lines indicate 0.5P, 1P, 1.5P, 2P,...,8P frequencies.

Parametric analysis – AR modeling

Upwind turbine – 8 m/s – 7D



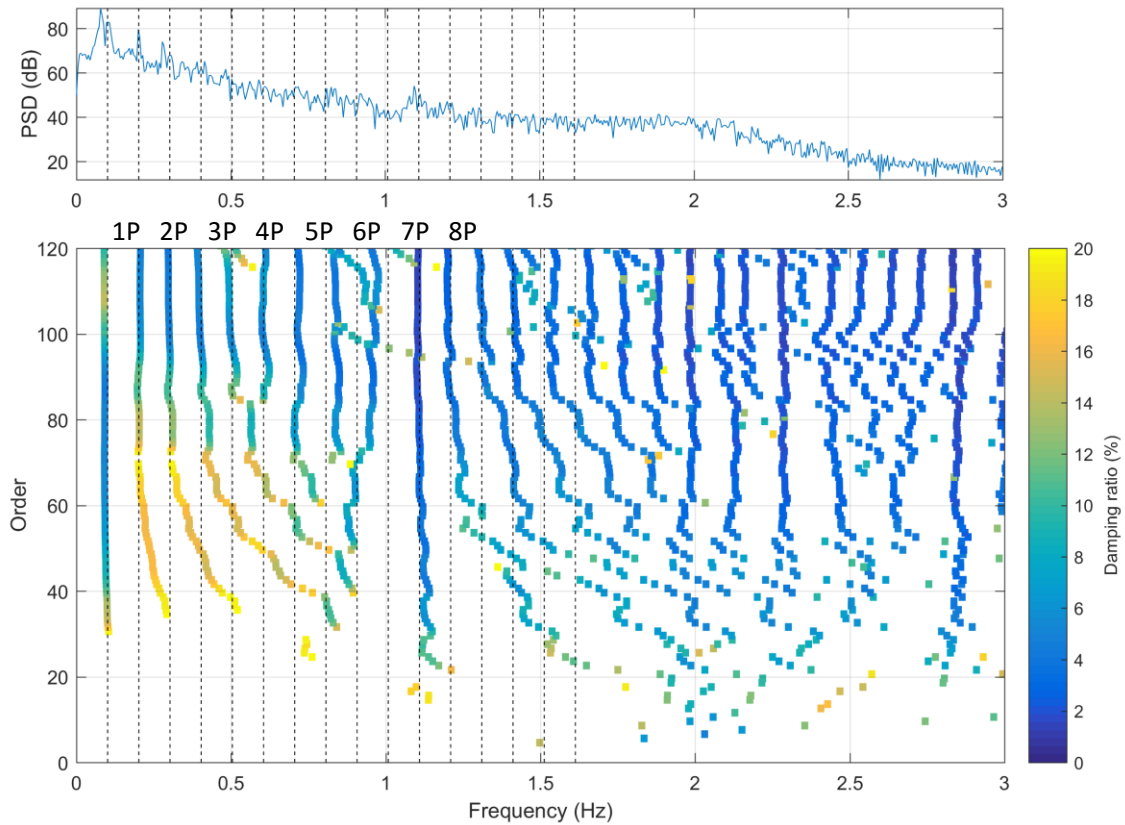
Downwind turbine – 8 m/s – 7D



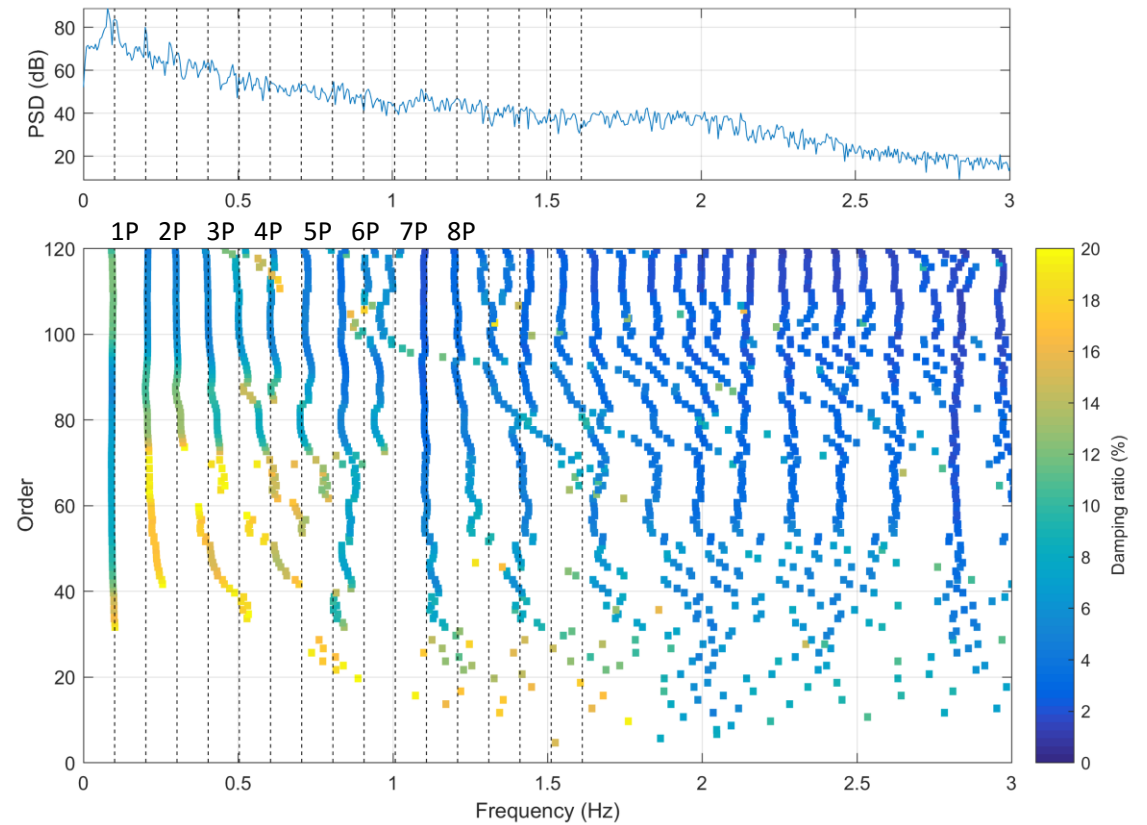
Modes with damping ratio under 20% are displayed. Vertical lines indicate 0.5P, 1P, 1.5P, 2P,...,8P frequencies.

Parametric analysis – AR modeling

Upwind turbine – 18 m/s – 2D



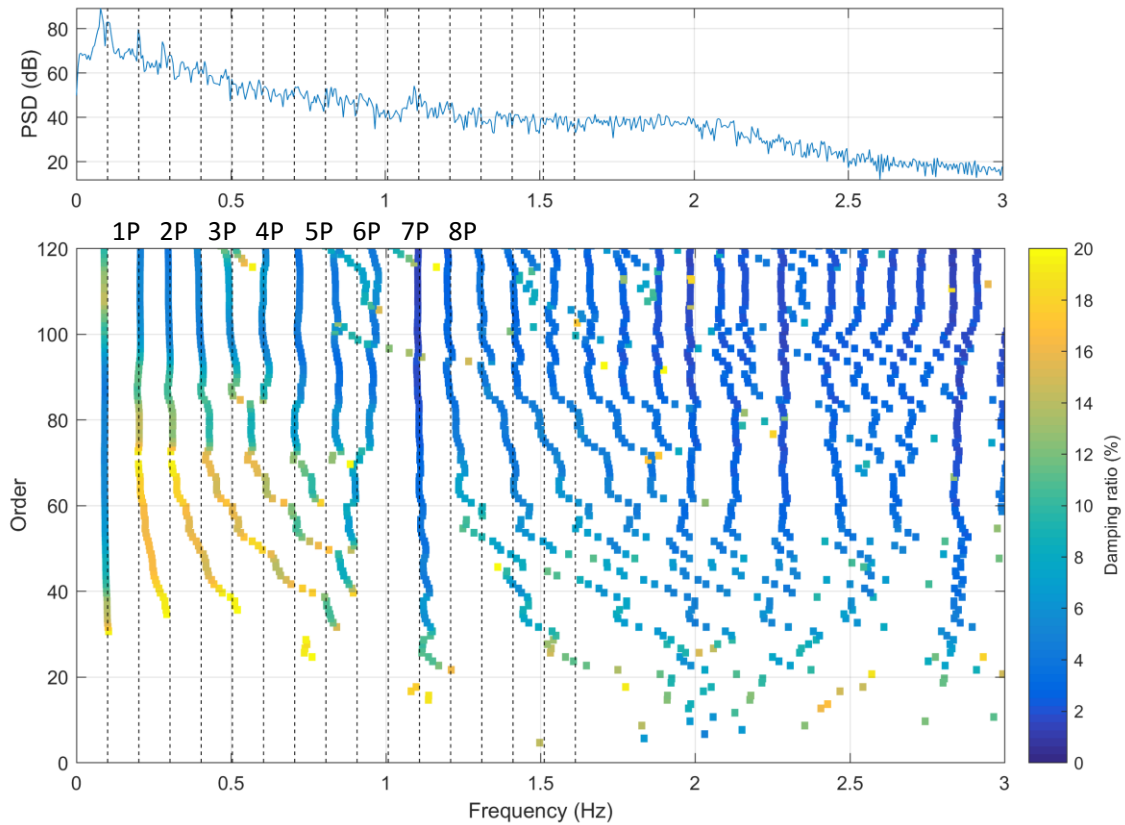
Downwind turbine – 18 m/s – 2D



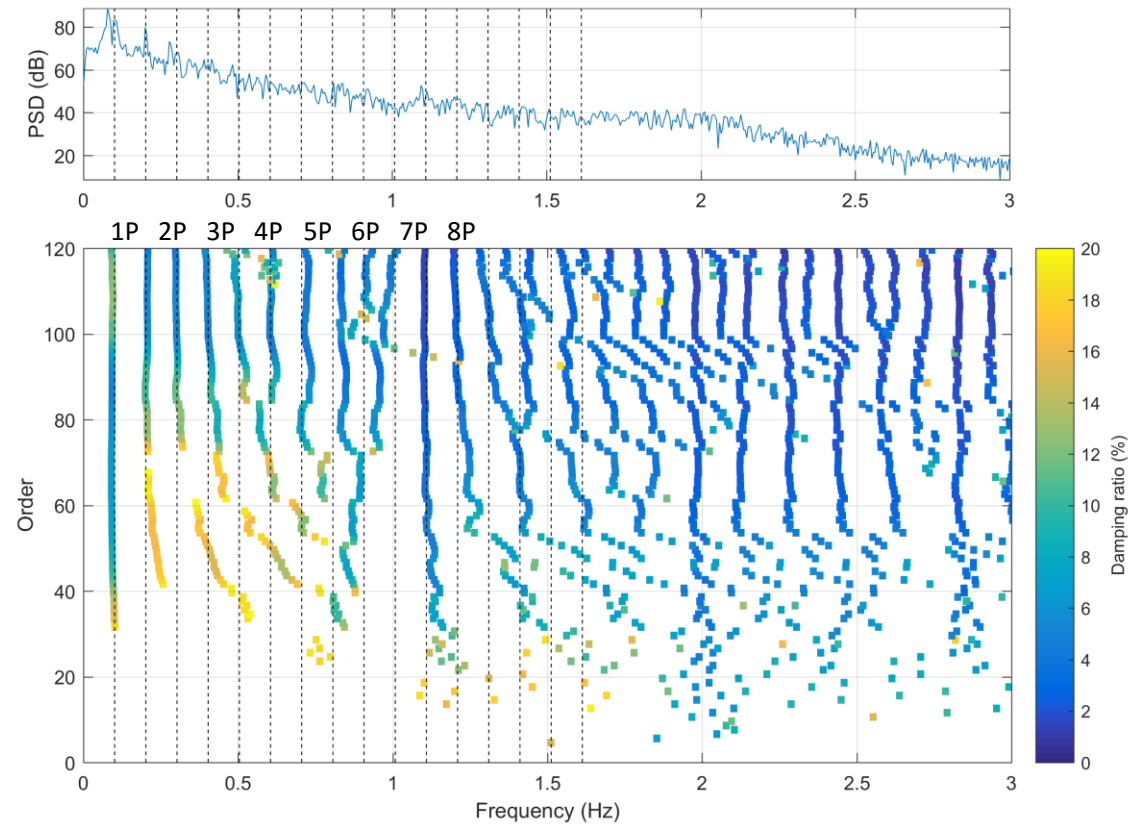
Modes with damping ratio under 20% are displayed. Vertical lines indicate 0.5P, 1P, 1.5P, 2P,...,8P frequencies.

Parametric analysis – AR modeling

Upwind turbine – 18 m/s – 7D



Downwind turbine – 18 m/s – 7D



Modes with damping ratio under 20% are displayed. Vertical lines indicate 0.5P, 1P, 1.5P, 2P,...,8P frequencies.

Parametric analysis – AR modeling

- Spectral content mainly dominated by the rotor frequency.
- Low wind speed:
 - Weak correspondence between frequency peaks and rotor frequency. Changing rotor speed modifies the position of the peak in the PSD.
 - Response on the downwind wind turbine at 2D and 7D cases is very different. Possibly because of different RPM.
 - 2nd blade flapwise mode is evident in both the frequency stabilization plot and PSD.
 - Several frequencies appear to be associated with harmonics of the sub-harmonic 0.5P. **Why?**
- High wind speed:
 - Strong correspondence between frequency peaks and rotor frequency. Rotor speed may be more stable.
 - The location of the main frequency peaks on 2D and 7D cases remains almost unchanged.
 - Structural modes are almost invisible

Final comments and observations

- Low wind speed case:
 - The larger differences observed in the PSDs of the upwind and downwind turbines may be due to the deficit in the average wind speed after the wake.
- High wind speed case:
 - The differences between the PSDs of the upwind and downwind wind turbines are less evident.
 - A large sample is necessary to determine if those changes are statistically significant.