Technical University of Denmark

46320: Loads, Aerodynamics and Control of Wind Turbines

Assignment 2

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1 Introduction

This report aims to describe the stability of a wind turbine design through the creation and examination of both structural and aeroelastic Campbell diagrams and analyze their implications for turbine stability.

In the first part, we estimate the structural Campbell diagram and compare it with HAWCStab2 results. And for the second part, we address aeroelastic effects by generating an aeroelastic Campbell diagram, analyzing the turbine's behaviour under operational wind speeds, and assessing the stability and resonance risk. The report will determine whether our turbine design is stable and if it presents resonance issues.

2 Part 1

The first step to analyze the structural response of the redesigned wind turbine is to create a .htc file that uses the information regarding the redesigned flexible blade, obtained in the previous assignment [3]. Hence this file can be opened using the HAWCStab2 program, and a structural modal analysis is performed for both the single blade and the entire turbine. The results are reported in Table 1. Note that the tower modal frequency is computed as the first modal frequency for the entire turbine, while the other values are found through the analysis of the single blade. The relative meaning was found by looking at the simulations generated by HAWCStab2 and comparing it to the theory [2]. For the entire turbine analysis, the meaning associated with each mode is defined in Table 2.

	tower	1st flap	1st edge	2nd flap	2nd edge
Modal frequency [HZ]	0.25	0.59	0.88	1.69	2.64

Table 1: Modal frequency and relative meaning for the single redesigned blade.

mode	1	2	3	4	5	6	7	8	9	10	11
meaning	t FA	t SS	1f BW	1f FW	1f S	1e BW	1e FW	/	/	/	drivetrain

Table 2: Relation between HAWCStab2 modes and relative physical meaning, with "t" for tower, "1f" for 1st flapwise, "1e" for 1st flapwise.

Hence, the turbine modal analysis can be performed for a rotating rotor. The resulting tower, 1st flap, and 1s edge natural frequencies and relative theoretical values are plotted in Figure 1. The theoretical curves are evaluated following Equation 1.

$$\omega_{n,S} = \omega_n, \qquad \omega_{n,BW} = \omega_n - \Omega, \qquad \omega_{n,FW} = \omega_n + \Omega \tag{1}$$

The computed tower frequencies align well with the theoretical values. However, all flapwsise modes start at a different value than the natural frequency of the flapwise blade (Table 3). This discrepancy is likely due to the substantial contribution of the tower, causing the standstill frequencies to differ from the single-blade frequency. Moreover, the symmetric mode increases with increasing rotational frequency: this is related to the phenomenon of rotational stiffening, in which centrifugal forces cause additional stiffness on a rotating body [1]. Similarly, the BW

and FW modes do not follow a linear trend, which can again be attributed to rotational stiffening.
On the other hand, the 1st edge backward and forward swirling align very well with the theoretical estimation. The symmetrical edge, also called drivetrain, on the other hand, does not follow Equation 1. In this particular mode, the boundary condition of the blade is altered (changing from fixed-free to pinned-free) and this increases the stiffness of the blade.

mode	single blade	BW	FW	S
frequency [Hz]	0.5903	0.522	0.569	0.613

Table 3: 1st flapwise modal frequency of the standstill turbine. Single blade computed analyzing only the blade, while Backward whirling (BW), Forward whirling (FW) and symmetrical (S) found as the first frequency (omega=0) for the analysis of the entire turbine.

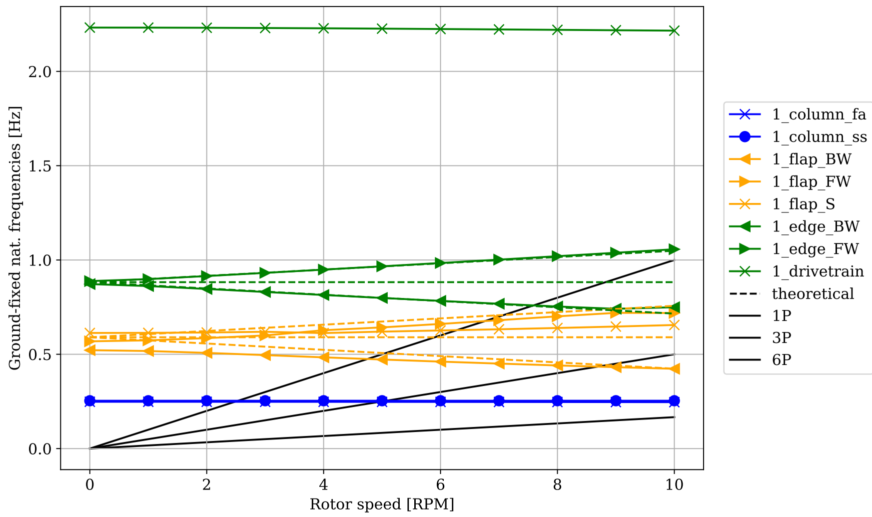

Figure 1: Structural Campbell diagram for the redesigned wind turbine.

The HAWCStab2 routine described earlier can be repeated, this time with the tower flexibility removed. The resulting graph is shown in Figure 2. Aside from the obvious absence of tower modes, there is a noticeable improvement in the agreement between the computed flapwise BW and FW modes and the theoretical curves. This supports the earlier assumption that the difference between the computed and theoretical flapwise frequencies in Figure 1 was due to the tower flexibility.

One final analysis can be performed by looking at the amplitudes of the modes. Using the function "plot_amplitudes" it is possible to create Figure 3. With this plot, the "relative meaning" previously assigned to the modes can be verified.

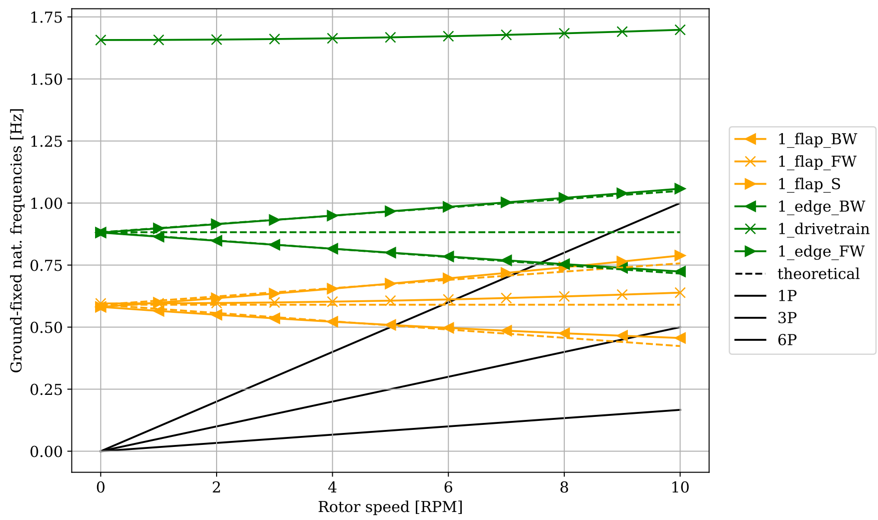

Figure 2: Structural Campbell diagram for the redesigned wind turbine, stiff tower.

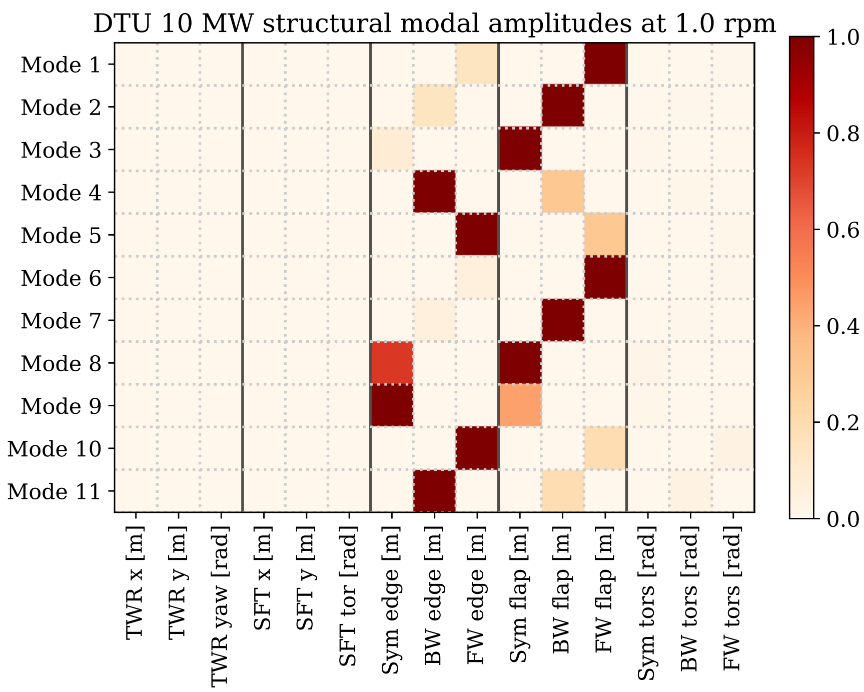

Figure 3: Amplitudes of the modes for the complete turbine analysis.

3 Part 2

In the next part of the assignment, the aeroelastic Campbell diagram is calculated. First, steady-state calculations need to be performed to calculate aerodynamic forces acting on the turbine for wind speeds of its operational range (4-25 m/s). This allows to calculate aerodynamic damping, which leads to a change in the natural frequencies of the modes. The resulting aeroelastic Campbell diagram is shown in Figure 4. The modes have been identified using Hawcstab2 and can be seen thanks to the heat map of the amplitudes of each mode at a wind speed of 4m/s, in Figure 5.

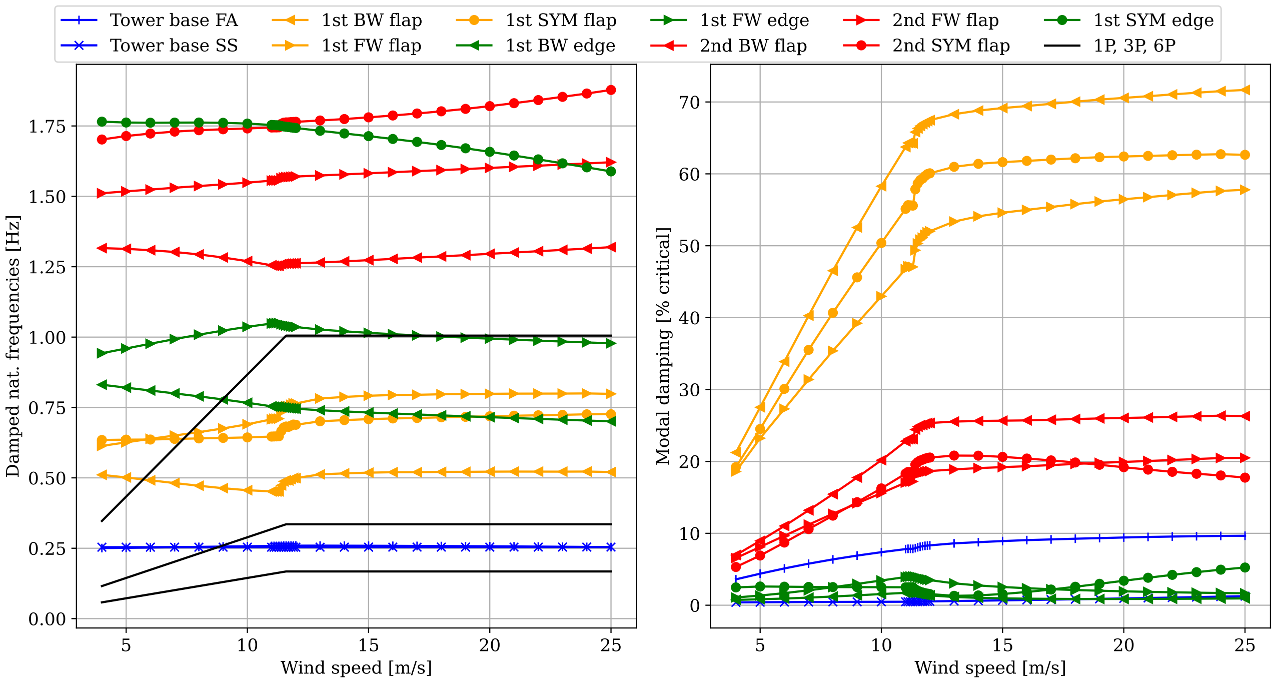

Figure 4: Aeroelastic Campbell diagram for the redesigned turbine.

In the aeroelastic Campbell diagram, the aerodynamic forces acting on the turbine influence its natural frequencies. The forces acting on the blades, i.e. lift and drag, increase with the wind speed below V_{rated}, leading to an increase in aerodynamic damping. When the blades start to pitch, lift and drag stop increasing, which corresponds to the flattening of the modal damping curve above V_{rated}. Moreover, when the blades start being pitched, a change in the natural frequencies of the modes follows.

The structural Campbell diagram included the frequencies related to the structural properties of the wind turbine, which don't change with the wind speed. The aeroelastic diagram represents the behaviour of the wind turbine during its operation. Adding aerodynamic forces results in a complete structural Equations of Motion 2, and additional EOMs to describe the aerodynamics of the turbine 3.

$$\mathbf{M}\ddot{x}_s + (\mathbf{C} + \mathbf{G} + \mathbf{C}_a)\dot{x}_s + (\mathbf{K} + \mathbf{K}_{sf} + \mathbf{K}_a)x_s + \mathbf{A}_f x_a = \mathbf{F}_s \tag{2}$$

$$\dot{x}_a + \mathbf{A}_d x_a + \mathbf{C}_{sa}\dot{x}_s + \mathbf{K}_{sa} x_s = \mathbf{F}_a \tag{3}$$

where:
$\mathbf{M}$ is the structural mass, $\mathbf{C}$ is the structural damping, $\mathbf{G}$ represents gyroscopic forces, $\mathbf{C}_a$ is the aerodynamic damping, $\mathbf{K}$ is the structural stiffness, $\mathbf{K}_{sf}$ is the geometric stiffness due to steady-state force, $\mathbf{K}_a$ is the aerodynamic stiffness, $\mathbf{A}_f$ is the coupling to aerodynamic states, x_s represents the elastic and bearing degrees of freedom, x_a represents the aerodynamic states, $\mathbf{F}_s$ is the force due to actuators, $\dot{x}_a$ represents time lags related to dynamic wake, $\mathbf{A}_d$ is the aerodynamic damping matrix, $\mathbf{C}_{sa}$ represents the coupling to structural states, and $\mathbf{F}_a$ is the aerodynamic force.

Additionally, aerodynamic damping is significantly greater than structural (as presented during the lecture), and only this kind of damping has been investigated in the report.

Lastly, the forcing frequencies for a single blade (1P) and the tower (3P, 6P) of the redesigned turbine were calculated and shown in Figure 4. It can be seen, that the 3P frequency intersects the tower base forcing frequencies, which might cause instabilities in the system at V=9 m/s, especially, since the tower side-side mode is only slightly damped. Similarly, the 6P frequency intersects all 1st flapwise and backward and forward 1st edgewise modes. The former are damped significantly, and after performing simulations of the performance of the turbine, the aerodynamic damping might be enough for a stable performance of the turbine. However, the edge modes undergo only slight damping and the resonance is likely. In consequence, adjusting the design of the turbine might be required or a minimum rotational speed might be introduced.

4 Conclusion

The first part analyzed the Structural Campbell diagram for the redesigned wind turbine with a flexible and stiff tower. It was noticed that the flapwise modes for the flexible turbine had different values compared to the natural frequency of the flapwise blade modes. It was however concluded that this difference was due to tower flexibility. The Aeroelastic Campbell diagram deduced that the 6P natural frequency intersected the first edgewise modes at a certain range of wind speeds. The 3P natural frequency also intersected the tower base frequency at a wind speed of 9 m/s. In conclusion, while the redesigned turbine shows overall promising performance, some instability risks remain, particularly related to resonance in the edgewise modes, which must be addressed for reliable long-term operation.

5 Appendix

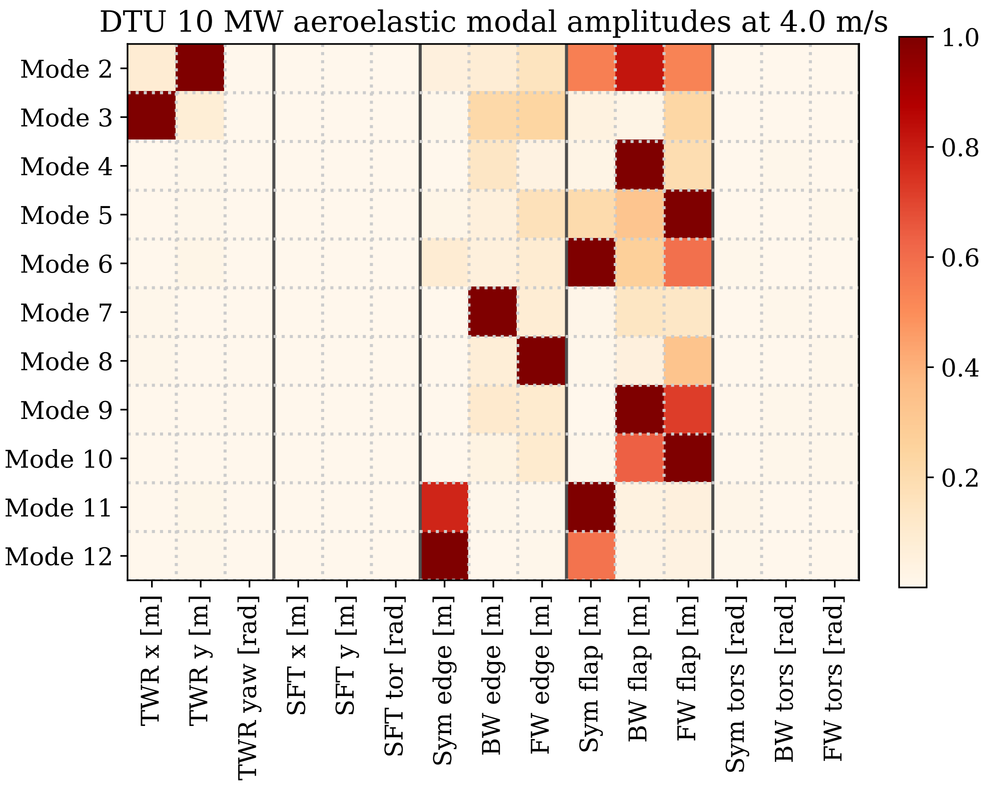

Figure 5: Amplitudes of the modes from the aeroelastic Campbell diagram for the complete turbine analysis

Bibliography

[1] Lokanna Hoskoti, Shakti S. Gupta, and Mahesh M. Sucheendran. “Modeling of geometrical stiffening in a rotating blade—A review”. In: *Journal of Sound and Vibration* 548 (2023), p. 117526. ISSN: 0022-460X. DOI: `https://doi.org/10.1016/j.jsv.2022.117526`. URL: `https://www.sciencedirect.com/science/article/pii/S0022460X2200709X`.

[2] Gunner Chr Larsen et al. “Modal analysis of wind turbine blades”. In: (2002).

[3] Nicola Quaia et al. *Aero-Elastic rotor design for Class IIIB, Group 1*. Sept. 2024.