Delft University of Technology

WIND TURBINE AEROELASTICITY

AE4W21-14

Instruction booklet of aeroelastic modelling assignment of a single blade

Instructor

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Assignment description

Form groups of three to complete this assignment. You can form groups on your own or use the discussion board on Brightspace to find groupmates.

Each group is tasked with creating an aeroelasticity model that simulates both time and frequency domain behaviors of one blade from the National Renewable Energy Laboratory (NREL) 5MW reference wind turbine. To model both in-plane and out-of-plane responses, the model should incorporate at least two degrees of freedom (DOFs): the first-order flapwise and edgewise DOFs.

You can calculate the aerodynamic loads using the Blade Element Momentum (BEM) theory (a BEM code will be provided; you may also choose another code if preferred). The assignment's primary objective is to determine the elastic deflections of the blade sections under aerodynamic loads. Establish the structural module using the Ritz method.

The below steps are recommended:

(1) Construct a structural model

Develop a structural model for an NREL 5MW wind turbine blade that includes stiffness K, mass M, and damping for flapwise and edgewise DOFs. The distributed "K" and "M" can be found in the slides of "structural dynamics" or in the report https://www.nrel.gov/docs/fy09osti/38060.pdf. The isolated blade's structural-damping ratio is 0.477465% for both modes. Calculate the first-order natural frequencies for both flapwise and edgewise modes.

(2) Couple the aerodynamic and structural modules

Coupling the aerodynamic and structural models using Eq. 1. BEM method calculates aerodynamic loads in the global rotor coordinate system, capturing the in-plane and out-of-plane responses. In contrast, flapwise and edgewise motions are defined in the blade's local coordinate system, with the section chord direction representing the edgewise direction and the perpendicular direction representing the flapwise direction. Therefore, it is important to differentiate between in-plane, out-of-plane, flapwise, and edgewise movements in the model.

$$\left\{ \begin{array}{c} V_{\text{inplan}} \\ V_{\text{outplan}} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ V_0 \end{array} \right\} + \left\{ \begin{array}{c} -r\Omega \\ 0 \end{array} \right\} + \left\{ \begin{array}{c} V_{\text{inplan-induced}} \\ V_{\text{outplan-induced}} \end{array} \right\} - \left\{ \begin{array}{c} V_{\text{inplan-blade}} \\ V_{\text{outplan-blade}} \end{array} \right\} \tag{1}$$

(3) Static wind

The wind turbine operates within a wind speed range of 3 m/s to 25 m/s. Calculate the flapwise deformations across this range of wind speed and simulate the blade responses at the wind speed of 15m/s. The rated wind speed for the NREL 5MW wind turbine is 11.4 m/s. Therefore, when the wind speed exceeds 11.4 m/s, you must account for the blade pitch angle. Refer to Table 1 for the relationship between wind speeds and the corresponding pitch angles.

Table 1: Pitch angles regarding wind speed

Wind Speed (m/s)	Pitch Angle (°)
11.4 - Rated	0.00
12.0	3.83
13.0	6.60
14.0	8.70
15.0	10.45
16.0	12.06
17.0	13.54
18.0	14.92
19.0	16.23
20.0	17.47
21.0	18.70
22.0	19.94
23.0	21.18
24.0	22.35
25.0	23.47

(4) Periodic wind

Assume the wind turbine is exposed to a periodic inflow wind condition where the inflow wind speed changes over time according to the function:

$$V_0(t) = 15 + 0.5\cos(1.267t) + 0.085\cos(2.534t) + 0.015\cos(3.801t) \tag{2}$$

According to Table 1, the pitch angle remains constant at 10.45°. Your task is to simulate the blade responses under the specified periodic wind conditions.

(5) Understand the role of blade deflections in wind turbine blade dynamics

The last term in Eq.1 captures the impact of blade deflection on aerodynamic loads. Your objective is to activate and deactivate this term and observe the resulting time-domain responses under the 'Periodic wind'. Evaluate how blade vibration velocities affect aerodynamic loads and blade movements. Does this term introduce extra damping for blade motions?

(6) Simulation of centrifugal and gravity stiffening

The lecture explains how the centrifugal and gravity forces impact geometric stiffness. Your task is to develop a function that accounts for these effects and analyze their influences. Conduct relevant analyses in frequency and time domains, with the time domain simulation based on the 'Periodic wind'.

(7) Simulate the unsteady loads due to dynamic stall and dynamic inflow

Implement the Beddoes-Leishman dynamic stall model and at least one of the dynamic inflow models. Assume the wind turbine is exposed to a wind speed of 15m/s and a harmonic collective pitch according to the function:

$$\text{Pitch angle}(t) = 10.45 + 5\sin(2\pi f t) \text{ [degree]} \tag{3}$$

where $f = 0.05, 0.2, 0.5$ $[Hz]$. The constants for the Beddoes-Leishman dynamic stall model can be the same used in the dynamic stall tutorial.

Deliverables

For this assignment, you need to write a scientific report and upload the report in Word or PDF format together with the code. The report needs to contain:

- A short introduction
- A flow chart(fluxogram) of your code.
- The natural frequencies of the blade.
- plots with explanation of the flapwise static deformation across wind speed ranging from 3m/s to 25m/s.
- plots with explanation of the blade's flapwise and edgewise root bending moment and tip deflection at the static wind speed of 15m/s in both time and frequency domains.
- plots with explanation of the blade's flapwise and edgewise root bending moment and tip deflection under the specified periodic wind in both time and frequency domains.
- plots with explanation of the blade's flapwise and edgewise root bending moment in both time and frequency domains and the maximal values of the radial distribution of blade flapwise and edgewise loads with/without considering the blade vibration velocity under the specified periodic wind.
- plots with explanation of the blade's flapwise tip deflection with/without considering the centrifugal and gravitational forces under the specified periodic wind in both time and frequency domains.
- (optional) Evaluate the level of unsteadiness of the rotor loads. Plots with explanation of the rotor thrust with respect to time and pitch angle with/without the dynamic inflow model. Discuss the dyanmic inflow effects on dynamic rotor responses.
- (optional) Evaluate the level of unsteadiness of the blade local loads. Plots with explanation of angle of attack, induction, the normal and tangential forces at 24.05m (Node 7) and 61.6333m (Node 17) with respect to time and pitch angles with/without the dynamic stall model. Discuss the dynamic stall effects on dynamic blade responses.

- discuss blade performance based on the results, including conclusions and potential recommendations for safe and efficient operation of the system.

Appendix

0.1 NREL 5 MW reference Wind turbine blade

This aeroelasticity model is based on the NREL 5MW wind turbine, and all the definitions used in this model are open-access. To assist you, we have gathered some relevant information.

The values of the spinning angular velocity at different wind speeds are listed in Table 2.

Table 2: Spinning angular velocity

Wind speed (m/s)	Spinning angular velocity(rad/s)
3	0.599
4	0.733
5	0.782
6	0.826
7	0.879
8	0.944
9	1.062
10	1.181
11	1.242
11.4	1.267
12	1.267
13	1.267
14	1.267
15	1.267
16	1.267
17	1.267
18	1.267
19	1.267
20	1.267
21	1.267
22	1.267
23	1.267
24	1.267
25	1.267

Table 3 presents the properties at 17 nodes, including their radial positions, radial lengths, chord lengths, twist angles, and airfoil geometries. The airfoil aerodynamic performance is provided along the code.

In addition, the mode shape functions for the wind turbine blades are defined as:

$$\begin{aligned} \phi_{1f}(r) &= 0.0622\left(\frac{r}{R}\right)^2 + 1.7254\left(\frac{r}{R}\right)^3 - 3.2452\left(\frac{r}{R}\right)^4 + 4.7131\left(\frac{r}{R}\right)^5 - 2.2555\left(\frac{r}{R}\right)^6 \\ \phi_{1e}(r) &= 0.3627\left(\frac{r}{R}\right)^2 + 2.5337\left(\frac{r}{R}\right)^3 - 3.5772\left(\frac{r}{R}\right)^4 + 2.376\left(\frac{r}{R}\right)^5 - 0.6952\left(\frac{r}{R}\right)^6 \end{aligned} \tag{4}$$

Table 3: Airfoil sections

Node (−)	RNodes (m)	AeroTwst (°)	DRNodes (m)	Chord (m)	Airfoil Table (−)
1	2.8667	13.308	2.7333	3.542	Cylinder1.dat
2	5.6000	13.308	2.7333	3.854	Cylinder1.dat
3	8.3333	13.308	2.7333	4.167	Cylinder2.dat
4	11.7500	13.308	4.1000	4.557	DU40_A17.dat
5	15.8500	11.480	4.1000	4.652	DU35_A17.dat
6	19.9500	10.162	4.1000	4.458	DU35_A17.dat
7	24.0500	9.011	4.1000	4.249	DU30_A17.dat
8	28.1500	7.795	4.1000	4.007	DU25_A17.dat
9	32.2500	6.544	4.1000	3.748	DU25_A17.dat
10	36.3500	5.361	4.1000	3.502	DU21_A17.dat
11	40.4500	4.188	4.1000	3.256	DU21_A17.dat
12	44.5500	3.125	4.1000	3.010	NACA64_A17.dat
13	48.6500	2.319	4.1000	2.764	NACA64_A17.dat
14	52.7500	1.526	4.1000	2.518	NACA64_A17.dat
15	56.1667	0.863	2.7333	2.313	NACA64_A17.dat
16	58.9000	0.370	2.7333	2.086	NACA64_A17.dat
17	61.6333	0.106	2.7333	1.419	NACA64_A17.dat

0.2 BEM code for aerodynamic loads determination

(1) This code has been developed based on the principles and theories outlined in Chapter 6 of the textbook 'Aerodynamics of Wind Turbines'.

(2) This code is designed to calculate the steady aerodynamic loads on the defined nodes. To obtain accurate results for different wind speeds, it is crucial to input the correct values for the blade rotational angular velocity and blade pitch angle. The blade rotational angular velocity, as well as the pitch angle, have been previously introduced in the earlier sections.