MECA0029–1 Theory of vibration

Analysis of the dynamic behaviour of an offshore wind turbine jacket

Academic year 2023 – 2024

Offshore wind turbines are built on different types of support depending on water depth, as depicted in Fig. 1. This work will focus on the jacket support and aims at describing its dynamic behavior. The theoretical subjects covered during the lectures of the course will be implemented to model the structure and to analyze its response to external loads.

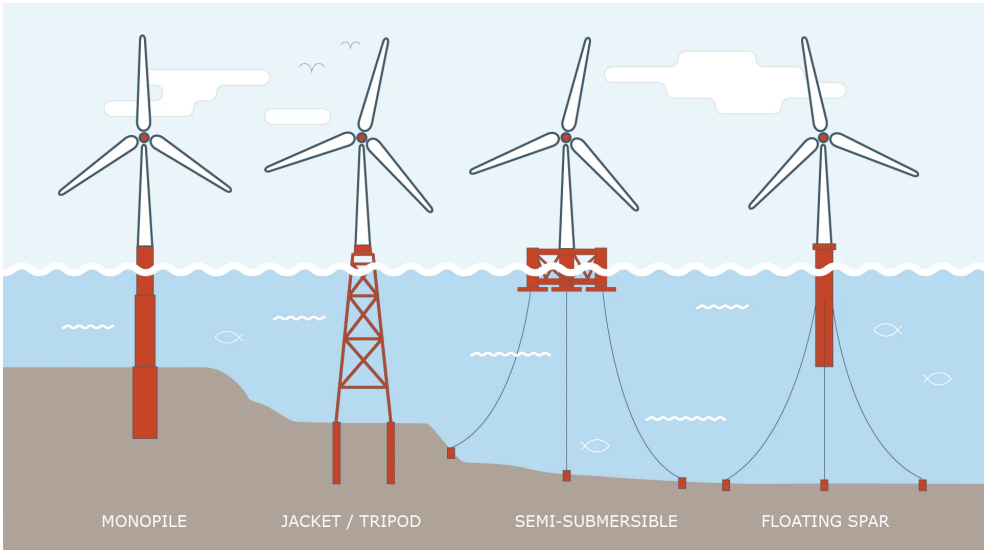


Figure 1 – Different types of offshore wind turbine supports (source: Cowi).

Work instructions

1. The work will be done **by groups of two students maximum**. A report will be submitted in which all the **descriptions**, **results** and **discussions** have to figure out. More information on the form of the report and evaluation criteria can be found on eCampus under "Objectives of the project".
   Reminder: a report must be written as a standalone work.

   - The report and the implementation (MATLAB/Python codes, NX files) have to represent your own work. **Any plagiarism will be severely punished**!
   - **40 pages** maximum are tolerated. You will be penalized if the report is too long (or extremely short).

2. The deadline for the submission of your work is fixed to **November 30, 2023** at **11:59 PM**. No additional delay will be tolerated.

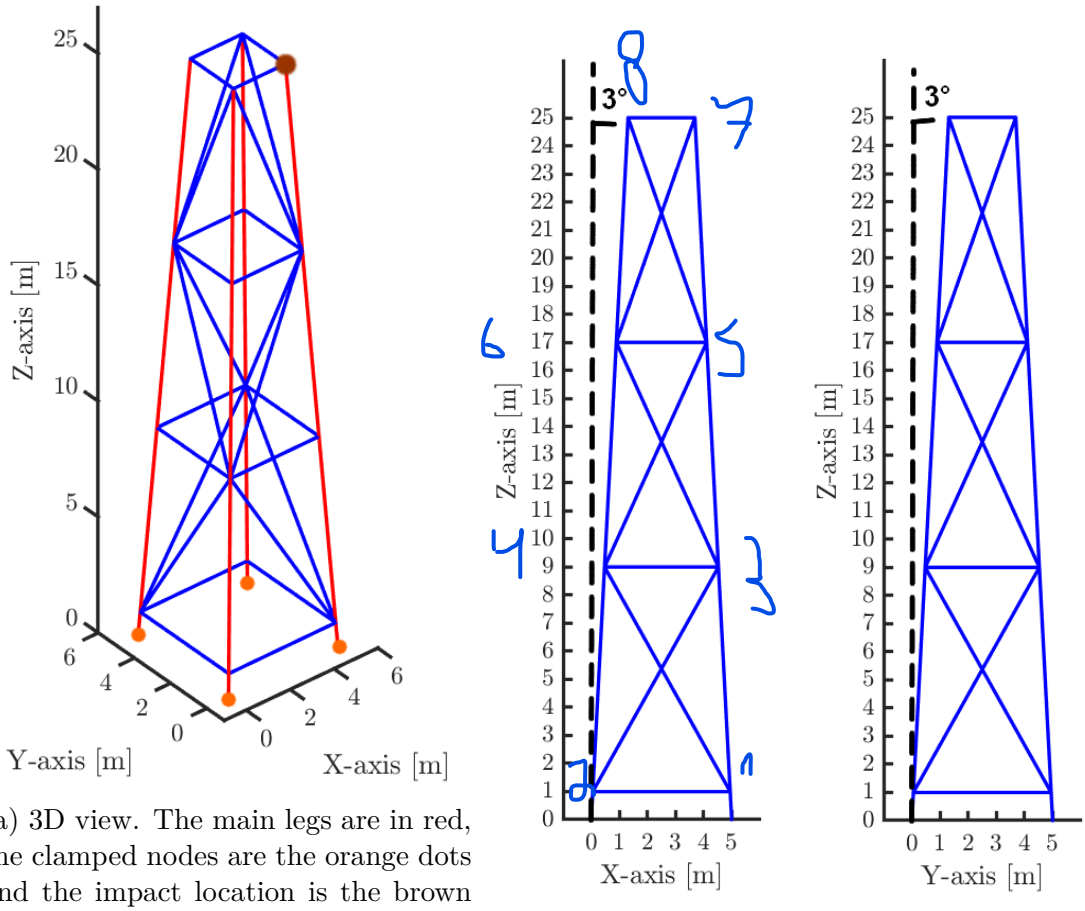
   Your work must be uploaded on eCampus. The report (.pdf) and an archive (.zip) containing the following must be provided:

   - The MATLAB/Python codes
   - The Siemens NX files (.prt, .fem and .sim only)

   For sorting purposes, name your main files as follows:

   - Report: `MECA0029_Group_XX.pdf`.
   - Siemens NX file (.sim): `MECA0029_Group_XX.sim`.
   - MATLAB/Python files: the main files must be named `MECA0029_Group_XX_Y.m`, where XX is the number of your group and Y is the file number. You can use and name other files and subfunctions at your own convenience.

1 : 5 5 1
2 : 0 0 1
3 : 4.58 4.58 9
4 : 0.42 0.42 9
5 : 4.16 4.16 17
6 : 0.838 0.838 17
7 : 3.74 3.74 25
8 : 1.26 1.26 25



(a) 3D view. The main legs are in red, the clamped nodes are the orange dots and the impact location is the brown dot.

(b) XZ view.

(c) YZ view.

Figure 2 – Jacket model.

1 Modeling of the structure

Recommended deadline: October 19, 2023

The structure to study is a simplified model of a jacket. It is built according to Fig. 2. It is composed of three main cells. Each of them is 8 [m] high for a total height of the structure of 25 [m]. At the bottom, the main legs, colored in red in Fig. 2a, form the vertices of a square whose side length is 5 [m] and they make an angle of **3 degrees** with respect to the vertical Z-direction.

All the beams of the truss are made of steel with the following material properties:

- Density: $\rho = 7800$ [kg/m^3].
- Poisson's ratio: $\nu = 0.3$ [-].

- Young's modulus: $E = 210$ [GPa].

They are assumed to have a **circular hollow cross-section**. The main legs have a diameter of 1 [m], whereas all the other beams have a diameter of 0.6 [m]. The thickness of the walls is 2 [cm] for all the beams.

The jacket legs are **clamped** at the bottom, as represented by the orange dots in Fig. 2a.

In order to simulate the presence of a wind turbine on the jacket, five **rigid links** are introduced as shown by the green lines in Fig. 3. Their properties are approached by the following beam properties:

- Density: $\rho_r = \rho \times 10^{-4}$ [kg/m^3].
- Poisson's ratio: $\nu = 0.3$ [-].
- Young's modulus: $E_r = E \times 10^4$ [GPa].
- Cross-section area: $A_r = A \times 10^{-2}$ [m^2].
- Area moments of inertia: $I_{yr} = I_y \times 10^4$ and $I_{zr} = I_z \times 10^4$ [m^4].
- Torsional inertia: $J_{xr} = J_x \times 10^4$ [m^4].

where the reference values A, I_y, I_z and J_x are the ones computed for the **main legs**[1].

At the end of the last rigid link, at a height of 80 [m], the rotor-nacelle assembly is represented by a **lumped mass** with a total mass $M = 200\,000$ [kg] and rotational inertias $J_x = J_y = J_z = 24\,000\,000$ [kg $\cdot$ m^2]. We will refer to this point as the "**rotor location**".

It is asked to

- Build the jacket model in **NX** based on 3D beam elements and extract the first **eight natural frequencies** along with their corresponding **mode shapes**.
- Build the jacket model in **MATLAB/Python** using the 3D beam model seen in the theory, extract the first **eight natural frequencies** and draw the corresponding **mode shapes** of the jacket.
- Make a **convergence study** (as a function of the number of elements per beam) in **both software**.
- Compute the **total mass** of the jacket-wind turbine assembly using a rigid-body mode in translation.

[1] The cross-section area A_r is not compatible with the inertias J_{xr}, I_{yr} and I_{zr}. This is not a mistake. In our case, the only aim of these properties is to build very light and stiff beams.

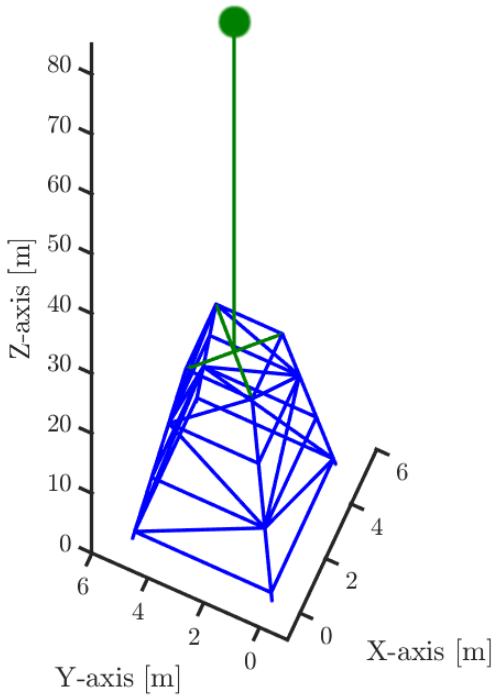


Figure 3 – Rigid links (green lines) and lumped mass (green dot).

2 Transient response

Recommended deadline: November 16, 2023

A seal is the target of a gang of killer whales and found refuge on top of the jacket. In order to try to make their prey fall from the structure, the killer whales start impacting the jacket (initially at rest) repetitively with their tail. The gang is astonishingly well organized, such that the resulting force on the jacket can be assumed to be a **sine** wave with a frequency of **1** [**Hz**]. The weight of their tail is **1** [**t**] and the velocity at the time of the impact is **25** [**km/h**]. We will consider that the impact lasts **0.05** [**s**]. In order to compute the amplitude of the sine wave, we make the assumption that **85 %** of the initial tail momentum is transferred to the jacket. The direction of the force forms an angle of **45 degrees** with the X-axis, as shown in Fig. 4. The impact point is visible in Figs. 2a and 4. Damping will be introduced in this part.

It is asked to (in MATLAB/Python)

- Compute the **damping matrix** using the **proportional damping** assumption such that the damping ratio of the **first two** modes is equal to **0.5 %**. List the damping ratios for modes 1 to 8.
- Compute an approximate solution using the **mode displacement** method. Plot the **time** evolution **in the direction of the impact** both at the **excitation point** and at the **rotor location**.
- Compute an approximate solution using the **mode acceleration** method. Plot the **time** evolution **in the direction of the impact** both at the **excitation point** and at the **rotor location**.
- **Compare** the results and discuss the **convergence** in terms of the number of modes included in the superposition.
- Compute the solution by time integration using the **Newmark** algorithm. **Justify** the choice of the time step and integration parameters. Plot the **time** evolution **in the direction of the impact** and its corresponding **FFT**, both at the **excitation point** and at the **rotor location**.
- **Compare** the result obtained through numerical integration with the ones obtained with approximation methods.

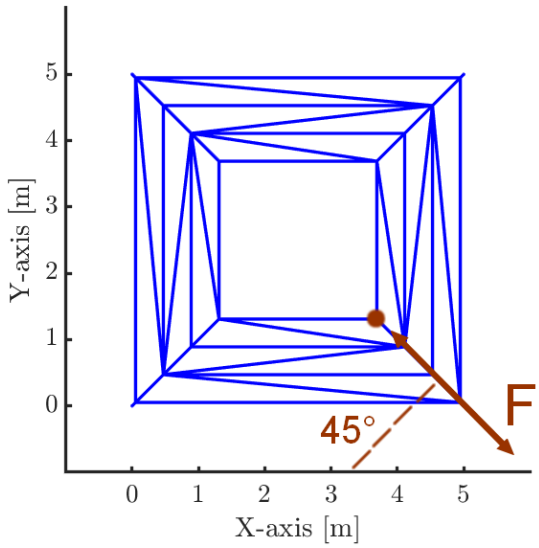


Figure 4 – Impact location (brown dot) and direction (brown line).

3 Reduction methods

Recommended deadline: November 30, 2023

To decrease the number of degrees of freedom, a part of the structure is condensed and **only the translation degrees of freedom and the rotation about the Z-axis** of the **two** nodes highlighted in Fig. 5 are retained.

It is asked to (in MATLAB/Python)

- Use **Guyan-Irons** method and **compare** the natural frequencies with the **initial** finite element model.
- Use **Craig-Bampton** method and choose an appropriate number of modes such that the relative error on the eight previously identified natural frequencies is **less than 2 %**. **Compare** the results with the **initial** model and with **Guyan-Irons** method.
- Compute again the response to the killer whales attack using **Newmark** algorithm and the reduced order model. Show the interest of reduction methods by comparing the responses at the impact location and rotor location in terms of **accuracy**, **size of the problem** and **computation time**.

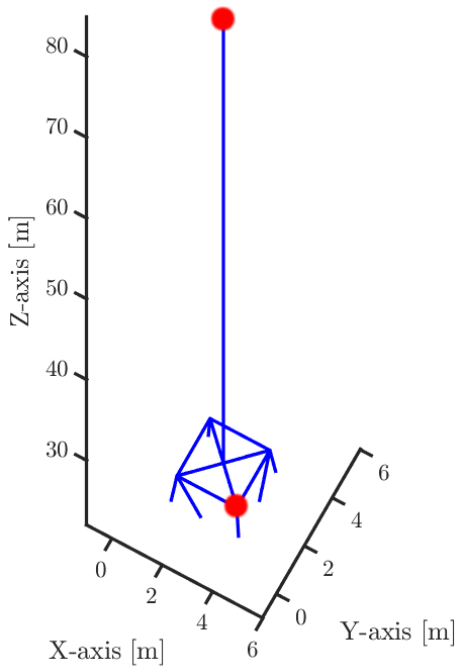


Figure 5 – Retained nodes for the reduction.