ASSIGNMENT – Floating offshore wind turbines

Introduction

In this assignment, we are going to study the turbine's response to a floating motion. For this, the NREL 5MW reference turbine installed on a semi-submersible floating structure, designed within the OC4 DeepCwind floating wind project [1], is used. The reference wind turbine has a rotor radius of 63m, a tower height of 90m and an overall rating of 5MW.

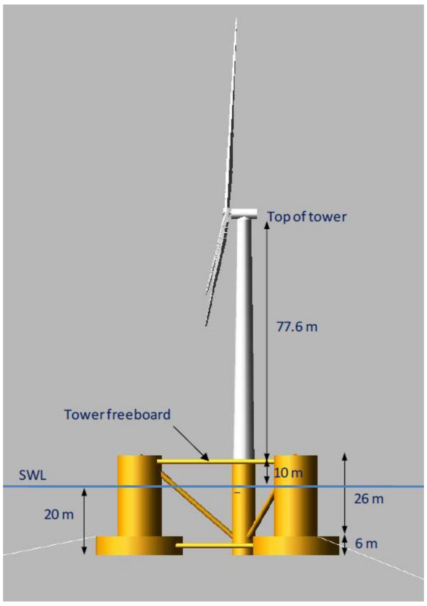

Figure 1: Design of the DeepCwind floating wind turbine system [1]

The purpose of this assignment is to get familiar with how floating turbines are moving as a result of imposed waves and to understand the effect of a floating motion on the loading and performance of the turbine. A BEM-based method, implemented in MATLAB, will be used and extended. First, the turbine will be subjected to a prescribed motion. Next, a realistic motion caused by regular waves will be coupled to the aerodynamic response of the turbine through the equations of motion. In the last part of this assignment, the results will be compared to the open-source aero-hydro-elastic simulation tool OpenFAST.

On Brightspace various documents are provided that will help you through this assignment:

- Framework for part 1: *main_part1.m*
- Framework for part 2: *main_ part2.m*
- Framework for part 3: *main_ part3*.m
- Turbine geometry: *NREL5MW.xlsx*
- Floater system matrices: *WADAM.mat*
- BEM function: *function_BEM.m*
- Define floater function: *function_floater.m*
- OpenFAST input files: *5MW_OC4Semi_WSt_WavesWN*
- OpenFAST V2.6 executable: *openfast/openfast_x64.exe*
- OpenFAST manual: *openfast/Documentation openFAST.pdf*

Deliverable

You are expected to write a concise report dealing with the topics/questions explained below. The report <u>cannot be longer than 20 pages</u> (from title up to the end of the reference list, font size minimum 11, single spacing). This excludes a print-out of your MATLAB code. You are allowed to work individually or in pairs. Please use the template to report your results. Your assignment should be submitted on Brightspace no later than <u>June 17th 2024 at 23:59</u>.

PART 1 – Wind turbine with prescribed motion

In the first part of this assignment, we will expose the NREL 5MW to a prescribed motion in pitch, surge and yaw. This will be done using a simple implementation of the blade element momentum (BEM) method. BEM methods, sometimes extended with various correction models, are often used in the wind turbine design process, due to its simplicity but still accurate results.

> TASK 1: Describe shortly the working principle and main equations of BEM in your report.

> TASK 2: Get yourself familiar with the BEM function (*function_BEM.m*) and the main script provided for PART1 (*main_part1.m*). A description of inputs/outputs is provided in the scripts. Complete the script to perform steady calculations of the NREL 5MW. Produce plots of the TSR-CT and TSR-CP curve and present them in your report.

Unfortunately, the provided BEM-code does currently not account for the effect of the floating motion. It is expected that, due to the floating motion, the relative velocity felt by the blades will be affected. It is your task to adjust the normal wind speed (Vn), where Vn will have 4 components:

$$V_n = V_{inf} - V_{surge} - V_{pitch} - V_{yaw}$$

> TASK 3: Adjust *function_BEM.m* and in particular the definition of the relative normal wind speed (Vn) for a given pitch, surge and yaw motion. You may apply the velocity component at the centre of the rotor (at the nacelle height) to all blade sections. Describe in your report what adjustments are made. (Tip: Vn is defined to be perpendicular to the rotor plane!)

The new BEM function can now be used in time to compute the unsteady response to a prescribed floating motion. A simple dynamic inflow model is already included in *function_BEM.m* to deal with transient (not instantaneous) responses of the turbine to changing inflow conditions. For this, the previous time step (PREVIOUSTIMESTEP in *function_BEM.m)* is required as input.

> TASK 4: Extend the main script provided for PART1 (*main_part1.m*) and write a routine to solve the unsteady BEM-function in time.

> TASK 5: Find a representative frequency and amplitude for the dominant floating motions for a semi-submersible floater in the literature. Apply these motions to the turbine and compute the aerodynamic thrust and power of the turbine in time. Discuss the applied motions and results in your report.

PART 2 – Wind turbine with coupled floating motion

The floating motion of a wind turbine is dictated by its floater and the waves. In the second part of the assignment, we will compute how the floater-turbine system reacts to various wave states. We are going to couple the hydrodynamic characteristics of the floater with the aerodynamic loads of the turbine by setting up the equations of motion. As discussed in the lecture, the equation of motion of a floater-turbine has the following overall shape:

$$(M + A)x'' + Bx' + (C + K)\,x = F_{ext}$$

Where M is the mass matrix, A is the added-mass matrix, B is the damping matrix, C is the hydrostatic matrix and K the mooring line stiffness matrix. F_{ext} consists of the external forces applied to the system and as such contains both the aerodynamic and hydrodynamic forces. x are the states and include the 3 translations and 3 rotations around the x, y and z axis, respectively. The origin is set at the bottom of the tower, 90 m below the center of the rotor.

> TASK 6: Describe shortly the equations of motion (Ax''+Bx'+Cx = F) of a floater-turbine in your report. Discuss the meaning of the various matrices and discuss their dependency on wave input. Also add a drawing including the positive direction of each state.

To be able to set up the equations of motion, more information is required for the floater. The hydrodynamic loads F_{hydro} as well as the added mass matrix A and damping matrix B are computed for you using the program WADAM [2]. WADAM is a hydrodynamic tool used to analyse the interaction of (regular) waves at various frequencies with offshore structures. It is a potential flow solution combined with Morison's equation for the viscous terms.

> TASK 7: Get yourself familiar with the main script provided for PART2 (*main_part2.m*). A description of inputs is provided in the scripts. The properties of the floater are loaded in the script (line 45-51 in *main_part2.m*) using the function *function_floater.m*. This function starts with reading in the WADAM data (*WADAM.mat*), and continues by extracting the matrices at the correct wave frequency by interpolation.

With the rotor, floater and inflow wind and waves defined, we are able to set up the equations of motion and consequently solve them. Basic mathematic books will help you on how to solve a second-order differential equation (or see extra document, page 5). You will have to define an initial condition for all states and its derivative. For now, assume that the external forces (F_{hydro} and F_{aero}) are zero.

> TASK 8: Extend the main script provided for PART2 (*main_part2.m*) and write a routine to set up the equations of motion and solve them in time.

To verify your implementation, some sanity checks can be performed. First, check if in absence of any external forces or distortion in the initial conditions, the system remains steady at its initial location and the outcome of all states is zero at all time. Further, we can perform free decay tests. Free decay tests show the response of your system when a distortion is introduced to the initial conditions. From an experimental test executed in the OC5 project [3], we learned that the natural period for the 6 states of the NREL5MW semi-submersible floater are:

Surge	Sway	Heave	Roll	Pitch	Yaw
106.7 s	112.3 s	17.5 s	32.8 s	32.5 s	80.8 s

> TASK 9: Execute free decay tests for pitch, surge and heave and compare your results with the experimental data. Discuss in your report your decay tests and the results in terms of natural frequency and damping. (Tip: we do not expect a perfect match with the experiments)

So far, no external forces were considered. However, to be able to determine the full aero-hydro response of the system, the aerodynamic and hydrodynamic loads should be applied to the system. The hydrodynamic loads can be defined by:

$$F_{hydro} = A \cdot WA \cdot \cos(kx - \omega t - \phi)$$

where A is the force amplitude per 1m wave amplitude (*FLOATER.Fhydrodynamic* in the script), WA is the wave amplitude, k is the wave number of the waves, ω is the wave frequency and ϕ is the force phase (*FLOATER.Fhydrodynamicphase* in the script). x is the turbine position in x-direction and t is the time.

The aerodynamic loads can be determined using the BEM code. Use here your adapted BEM model from task 3, as this one accounts for the effect of the floating motion (surge, pitch and yaw). Transform the thrust force, acting perpendicular to the rotor disk (!), to a force in x, y and z and a moment around the x, y and z axis at the bottom of the tower. You may assume that the thrust force acts in the centre of the rotor disk. You may assume small angle approximations for pitch and yaw.

TASK 10: Extend the main script provided for PART2 (*main_part2.m*) and include the aerodynamic and hydrodynamic forces into the equation of motion.

TASK 11: Compute the response of the turbine to various sea states. Some definitions of various sea states can be found in the OC4 project description [1] and are repeated below. For sea state values below 2, the sea is considered calm. Starting from a sea state of 5, sea conditions could be considered rough. Discuss in your report your results in terms of motion and turbine performance/loading.

Sea state	Wave period, T [s]	Wave height, H [m]
1	2.0	0.09
2	4.8	0.67
3	6.5	1.40
4	8.1	2.44
5	9.7	3.66
6	11.3	5.49
7	13.6	9.14
8	17.0	15.24

PART 3 – Compare with OpenFAST and identify limitations

In the third and last part of the assignment, we will validate our newly developed simulation tool. This will be done by comparing the floating motion and turbine performance with results from OpenFAST. OpenFAST enables coupled nonlinear aero-hydro-servo-elastic simulation in the time domain. It allows multi-physics, multi-fidelity simulations of the coupled dynamic response of (floating) wind turbines. On Brightspace, the (freely available) executable of the simulation tool (*openfast_x64.exe)* as well as example input files (*5MW_OC4Semi_WSt_WavesWN*) for the NREL 5MW wind turbine are provided, but they may also be downloaded from Ref. [4]. We also provided a Matlab code (*main_part3.m*) that may be used to call the executable through Matlab.

The overall set-up of OpenFAST is sketched in Figure 2. In this assignment, we do not expect you to understand all input parameters, however, you are urged to make yourself familiar with the input files and structure of OpenFAST. The overall simulation set-up is defined in the *.fst file.* The OpenFAST example uses similar fidelity methods as used in your newly developed code. It uses BEM theory for the aerodynamic calculations (but includes various correction models) and the hydrodynamics builds on the frequency-to-time-domain transforms of potential flow calculations. Note that in the example input files the blades, tower, drivetrain and generator degrees of freedom are disabled for simplicity. As such, the rotational speed of the turbine will remain constant and no blade nor tower deflection is considered.

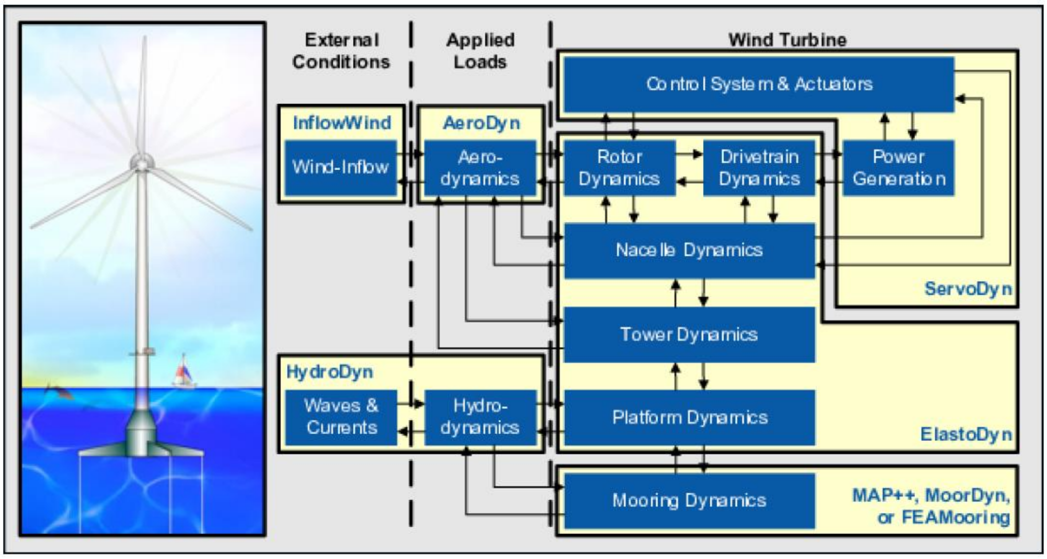

Figure 2: OpenFAST set-up [4]

> <u>TASK 12</u>: Get yourself familiar with the run script provided for PART3 (*main_part3.m*). Try to run an OpenFAST simulation and study the output parameters.

The main purpose of this task is to validate our newly developed code. As such we will run simulations in similar wind-wave conditions.

> <u>TASK 13</u>: Search through the input files and find where you can adjust the inflow velocity and the incident waves. Set the inflow wind speed to a constant value of 10 m/s. The rotor rational speed may remain to 9 rpm. Set the waves (wave period and height) to match the different sea states. At least evaluate sea state 4, 5 and 6.

> <u>TASK 14</u>: Run the simulations and compare the results with your simulation code. Discuss in your report how well the platform surge, heave and pitch compare, as well as the turbine thrust and power. The thrust and power are no direct output from OpenFAST but may be derived from the aerodynamic moment around the x-axis (*OUTPUT.RtAeroMxh*) and the aerodynamic force is x (*OUTPUT.RtAeroFxh*). To improve the match between OpenFAST and your tool, we suggest to apply the exact wave-excitation force that is output from OpenFAST (*OUTPUT.B1WvsFxi, OUTPUT.B1WvsFyi, OUTPUT.B1WvsFzi, OUTPUT.B1WvsMxi OUTPUT.B1WvsMyi, OUTPUT.B1WvsMzi, ...*) to your system.

TASK 15: While the overall trend of the comparison is similar, there are still various discrepancies. Explain in your report some potential reasons. Relate this to various assumptions that have been made in your model.

Tips or frequently-asked questions:

- The example code is written in Matlab and runs on Windows. If you do not have access to a Windows laptop, you can use the TUDelft desktops.
- If the BEM code did not converge or encounters NaNs/complex numvers, you probably did something wrong. Do not ignore this error.
- When solving the differential equation according to the attached document, the exponential of the A matrix refers to the matrix exponential and not the exponential of each matrix element. In Matlab this is done using expm() and not exp().
- FLOATER.Fhydrodynamicphase is given in degrees.
- PREVIOUSTIMESTEP is a Matlab structure and consists of PREVIOUSTIMESTEP.a_new and PREVIOUSTIMESTEP.ap_new.

References

[1] A. Robertson, J. Jonkman, M. Masciola et al. Definition of the semisubmersible floating system for phase II of OC4, Technical report NREL/TP-5000-60601, 2014.

[1] C.H. Lee, Wamit, Theory manual, Massachusetts Institute of Technology, 1995.

[3] A. Robertson, J. Jonkman, F. Wendt et al. Definition of the OC5 DeepCwind sermisubmersible floating system, Technical report, 2017.

[4] National Renewable Energy Laboratory Openfast v2.6.0 github.com/openfast/openfast/ online; Accessed on 29-07-2021.