
Memorandum —Load Case 5.4 from OC3 Phase IV (Floating)

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To: IEA Task 23 OC3 Phase IV Participants
From: Jason Jonkman, NREL

Load case 5.4 from OC3 Phase IV (floating) has been defined as follows:

- Goal: To test the OC3-Hywind system's frequency response
- DOFs: All – platform, tower, drivetrain, blades
- Wind condition: Steady, uniform, no shear, $V_{hub} = V_r = 11.4$ m/s
- Wave condition: Regular Airy, $H = 2$ m (1 m amplitude), $\omega = 0.1, 0.2, \dots, 3.5$ rad/s (discrete frequencies to be analyzed in separate simulations)
- Turbine status: Operating with the control system enabled
- Simulation process: Simulate to a periodic quasi-steady condition and compare the “effective Response Amplitude Operators” (effective RAOs), which are the system's displacements and loads normalized by the wave amplitude (1 m) and compared versus wave frequency. The word “effective” is used to clarify that the results of this load case are not true RAOs when the underlying models are nonlinear.

At our OC3 net-meeting on October 15, we reviewed the discussion from our Stockholm meeting regarding the problems running this load case. To summarize, the problem is that there are multiple excitation frequencies in each simulation:

- a) The wave-excitation frequency ($\omega = 0.1, 0.2, \dots, 3.5$ rad/s, depending on the simulation)
- b) The rotor-rotational frequency (about 12 rpm = 1.257 rad/s)
- c) The platform-surge natural frequency (about 0.008 Hz = 0.05 rad/s). This frequency plays a role in the response because the simulation occurs at rated conditions with the control system active. And, even though the blade-pitch control gains have been detuned to eliminate the blade-pitch-controller-induced instability of the platform-pitch mode, the platform-surge mode is of lower frequency and therefore is slightly unstable in this condition. Because of the system's nonlinearities, this instability leads to a limit-cycle oscillation of the platform-surge mode when simulating at steady rated conditions. (This would be less of an issue when simulating below or above rated wind-speed conditions because the blade-pitch-controller is inactive below rated and the thrust is less sensitive to wind speed above rated.)

The multiple excitation frequencies are a problem because the quasi-steady response will not be purely periodic at the wave frequency, but will oscillate with a superposition of responses at the three dominant frequencies.

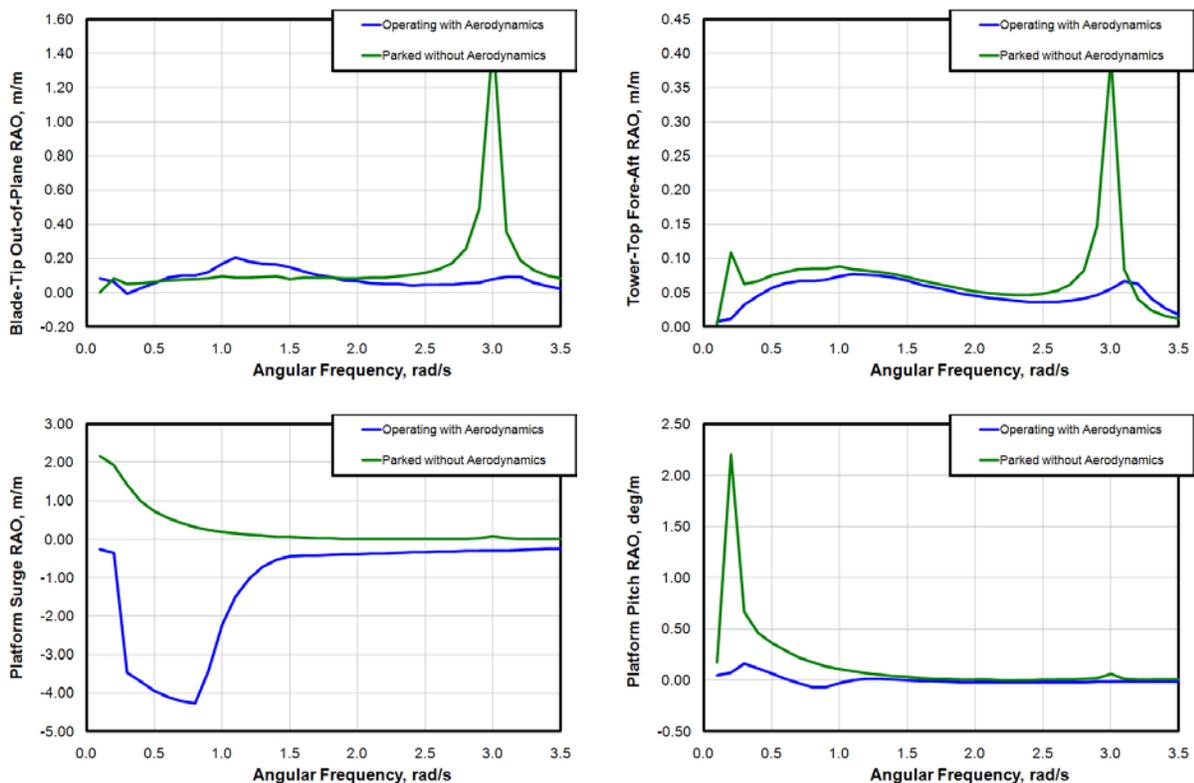
The solution I proposed to resolve this problem was a procedure for calculating an effective RAO, as follows:

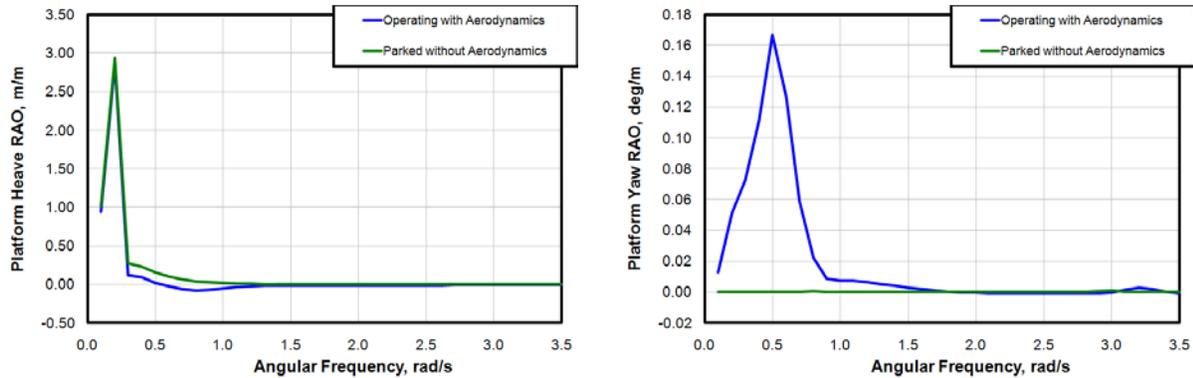
- 1) For each wave frequency, run a time-domain simulation for as long as it takes until all start-up transients have died out, giving a quasi-steady response.

- 2) Using the time-series data from (1), record the maximum value of the quasi-steady response, and subtract from it the minimum value of the response (i.e., record the overall range of the quasi-steady response).
- 3) Using the range from (2), subtract the range of the quasi-steady response from an equivalent simulation run without waves (i.e., a simulation run in still water).
- 4) Take the difference in ranges from (3) and divide by 2, giving the difference in amplitudes. The resulting value is the amplitude of the response induced by the wave excitation, which can be thought of as an effective RAO for this condition.
- 5) Repeat the calculations of steps 2-4 for each output parameter.
- 6) Repeat steps 1-5 with simulations at each wave frequency.

Karl Jacob Maus suggested that perhaps it would be simpler to calculate the effective RAOs with the rotor parked. I agreed that this would simplify the problem because the rotor rotational frequency and platform surge limit cycle-oscillation [frequencies (b) and (c) from above] would be eliminated, ensuring that the quasi-steady responses from each simulation would then be periodic at the wave frequency. However, this calculation would then miss the impact of the rotor rotation (i.e., gyroscopic loads) on the system's response, which I felt would be interesting to verify in our code-to-code comparisons because it is an interesting feature that is unique to floating wind turbines when compared to other floating structures.

Using FAST, I ran load case 5.4 using the stepwise procedure described above for both approaches—that is, with and without the turbine operating at rated. For the approach with the rotor parked, I also neglected aerodynamic loads. The results are shown next for several system displacements (out-of-plane blade-tip deflection, tower-top fore-aft deflection, platform surge, platform pitch, platform heave, and platform yaw).





The first thing to notice in these results is that the turbine operation has a dramatic effect on the system’s response. For the parked rotor, the effective RAOs are typical of floating platform RAOs—that is, the responses are largest at the system’s natural frequencies (about 0.034 Hz = 0.2 rad/s for platform pitch, 0.032 Hz = 0.2 rad/s for platform heave, and 0.46 Hz = 3.0 rad/s for 1st tower-bending). There are a few similarities between the parked and operating turbine effective RAOs—particularly in the tower-top fore-aft deflection and platform heave—but otherwise the two approaches produce quite different results. For the operating turbine, three atypical characteristics are noticed:

- 1) The effective RAOs can be negative in value—particularly in platform surge. This means, physically, that there is less platform-surge motion of the system when waves are present than there is in still water. The cause of this was discovered after a bit of research. In the still water simulation, the wave frequency is eliminated from the excitation/response. In the simulations with wave excitation, the wave-induced motions occur at the wave-excitation frequency, which brings about (potential-flow-based) wave-radiation damping. At the platform-surge natural frequency, the wave-radiation damping is negligible in all platform modes, as shown in Figure 4-4 of the OC3-Hywind specification report. In contrast, the wave-radiation damping is not negligible above 0.2 rad/s, extending to high frequencies for the platform-surge mode, but becoming negligible above about 2.5 rad/s for the platform-pitch mode (again, see Figure 4-4 from the OC3-Hywind specification report). This wave-radiation damping reduces or eliminates the platform-surge instability (depending on the wave-excitation frequency) and resulting limit-cycle oscillations [frequency (c) from above], thereby reducing the overall motions considerably.
- 2) There are noticeable broad-banded “features” in the effective RAOs between 0.3 and 1.2 rad/s, where there is no natural frequency in the system (except platform yaw at about 0.12 Hz = 0.75 rad/s)—particularly in the platform-surge, -pitch, and -yaw motions. The explanation for this is related to characteristic (1), described above. That is, the wave-radiation damping is highest in the frequency range of the effective RAO features (again, see Figure 4-4 from the OC3-Hywind specification report). Although the results are not presented here, it is noted that the mean values of the responses are also quite different between the simulations with and without waves in the frequency range of the effective RAO features.
- 3) There is noticeable excitation of the platform-yaw mode. This is caused by gyroscopic loading from the spinning rotor combined with platform pitching.

Due to the strong influence of the (potential-flow-based) wave-radiation damping in these results, it is noted that codes that neglect this damping will likely predict vastly different effective RAOs.

Given these results, the following options (and perhaps more) could be considered for load case 5.4 by the OC3 Phase IV participants:

- 1) Run load case 5.4 using the stepwise procedure described above for the case as originally defined (with the turbine operating at rated as presented in the results above)
- 2) Run load case 5.4 using the stepwise procedure described above for the parked rotor without aerodynamics (as suggested by Karl Jacob Maus and presented in the results above)
- 3) Run load case 5.4 using the stepwise procedure described above for an operational case below or above rated wind speed—say at 8 m/s or 18 m/s. In this situation, the platform-surge instability induced by the control system will be less severe or nonexistent, thereby reducing or eliminating the resulting limit-cycle oscillations [frequency (c) from above] (the results of such a load case are not shown here)
- 4) Drop this load case all together from the set of OC3 Phase IV simulations.

We will discuss these results and options at our next OC3 net-meeting.

If you have questions, please contact me:

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