Investigation of Response Amplitude Operators for Floating Offshore Wind Turbines

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ABSTRACT
This paper examines the consistency between response amplitude operators (RAOs) computed using a linear frequency-domain tool to RAOs derived from time-domain computations based on white-noise wave excitation using FAST, a nonlinear aero-hydro-servo-elastic tool. The RAO comparison is first made for a rigid floating wind turbine without wind excitation. The investigation is further extended to examine how these RAOs change for a flexible and operational wind turbine. The RAOs are computed for below-rated, rated, and above-rated wind conditions. The method is applied to a floating wind system composed of the OC3-Hywind spar buoy and NREL 5-MW wind turbine. The responses from the two approaches are compared to verify the FAST model, and to understand the influence of structural flexibility, aerodynamic damping, control actions, and waves on the system responses. The results show that based on the RAO computation procedure implemented, the linear frequency-domain and time-domain approaches produce similar RAOs (as expected) for a rigid turbine in waves. However, linear frequency-domain tools are unable to model the excitation from a flexible turbine. Further, the presence of aerodynamic damping decreased the platform surge and pitch responses when wind was included. Additionally, the influence of gyroscopic excitation increased the yaw response, which was captured by both methods.

KEY WORDS: Floating offshore wind turbines; OC3-Hywind spar; response amplitude operator; RAO.

INTRODUCTION
Response amplitude operators (RAOs) are conventionally the frequency response functions, which are simply the ratio of the output to a given input. RAOs are used in the offshore oil and gas industry to assess the frequency-domain linear wave-body response of floating platforms during the design process. RAOs also have been applied in the design of floating platforms for wind turbines; but, in offshore floating wind turbines, in addition to the hydrodynamic loading, aerodynamics, structural dynamics (including blade and tower flexibility), and controller dynamics also are important effects. Due to the inherent nonlinearities of these dynamics, offshore floating wind turbines are designed and analyzed with nonlinear time-domain aero-hydro-servo-elastic tools. It is important to understand how these additional dynamics affect the system responses. Due to sophistication of the nonlinear time-domain aero-hydro-servo-elastic tools, it also is essential that—before the models are applied in a design—the responses are verified as being meaningful. As such, it is important to compare the responses predicted from the complicated nonlinear time-domain tool to the responses predicted from a simpler model.

As floating wind turbines are receiving more attention, it is necessary to determine measures to describe the motion characteristics of each of the concepts when subjected to both wind and wave loading. A popular tool for computing RAOs of offshore platforms is WAMIT (referred to as “LFD Program” (linear frequency-domain program) hereafter), a three-dimensional panel code used to compute the linear wave forcing and motion characteristics of an offshore structure in the frequency domain (Lee and Newman, 2006). However, the motion characteristics of a floating platform for a deep-water wind turbine are also influenced by the structural flexibility and the operational conditions of the wind turbine, including aerodynamics and controller-induced motion. It is not possible for linear frequency-domain tools to capture the interaction of the flexible wind turbine degrees of freedom (DOFs) with the platform motion in the computation of RAOs or system nonlinearities. This is overcome by interfacing the LFD Program with the nonlinear time-domain aero-hydro-servo-elastic tool, FAST (Jonkman and Buhl, 2005), developed by the National Renewable Energy Laboratory (NREL). FAST can model the nonlinear dynamics of the flexible wind turbine subjected to hydrodynamic and aerodynamic excitation, and can compute the RAOs of the complete offshore wind system through white-noise wave excitation and the associated time-domain responses.

The purpose of this investigation is to examine a proposed procedure for verifying floating offshore wind system models built in FAST, and to understand the influence of structural flexibility, aerodynamic damping, control actions, and waves on offshore floating wind system response. The verification procedure involves comparing RAOs generated from FAST to those generated from a frequency-domain-only tool for a rigid offshore wind system. After the verification is completed, flexibility is added to the wind turbine in FAST and cases including wind excitation are used to understand the influence of these conditions on the RAOs.

A diagram of the two methods examined in this paper for computing RAOs is shown in Figure 1. A detailed description of the RAO computation procedures using a LFD Program and FAST is given in the next sections.