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A new method for radiation forces for floating platforms in waves

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ABSTRACT

The performance of wave energy converters and other offshore renewable energy platforms, non-linear effects is frequently assessed in time domain, especially when the nonlinear forces from the large amplitude motions, mooring forces, power take-off or the energy conversion control system are considered. One popular approach in the time-domain analysis is the so-called hybrid frequency–time domain analyses, in which the radiation forces must be calculated through a convolution integral of the motion history and the impulse response function. The direct integration of the convolution is not only time-consuming and inconvenient when a real time control is used, but also needs a storage and renewal of a certain history of motions. To this end, some approximation methods have been developed for calculating the memory effect, and these methods inevitably introduce additional equations into the dynamic system. In this paper, a new method is proposed for calculating the memory effect by extending the conventional Prony's function method so that the memory effect calculation can be carried out simply in a recursive manner. As a result of the recursive calculation, only one previous step of the values is needed, which can be renewed automatically in each time step calculation.

1. Introduction

In developing a wave energy converter, its assessment is an important but rather difficult issue. Principally, the assessment can be done either through a well-developed numerical tool or a proper scaled physical model. In the earlier stages of the development, numerical simulations may be more frequently used due to its nature of fast turnaround and low cost. However, for floating structures, including wave energy converters and other offshore renewable energy platforms, non-linear effects, such as the non-linear forces from the large amplitude motions, mooring forces, power take-off or the energy conversion control system must be included in the numerical analysis for the entire dynamic system, and therefore, a time domain analysis is usually carried out.

For the conventional ocean platforms or floating platforms for wind turbines or many other floating structures, the design philosophy is to obtain the small amplitude motions in waves. It is frequently done by designing a floating structure having a much larger or smaller resonance frequencies than those in the energetic waves. However, for wave energy converters, in order to extract more energy from waves, the wave energy converters are normally designed to have resonance frequencies to the energetic waves, so large amplitude motions and energy extraction can be achieved. Obviously, the large amplitude motions can generate some nonlinear effects. For example, the mooring system and restoring forces under the large amplitude motion can be nonlinear, see (Fitzgerald and Bergdahl, 2008) and (Sheng et al., 2011). For wave energy converters, it is frequent to see that the power take off system may provide additional nonlinear forces on the dynamic system, because in some cases a nonlinear PTO is preferable. It has been shown that a real-time/online control strategy is also popular for improving wave energy conversion, which will inherently introduce nonlinear forces into the system, regardless of the controlled PTO being linear or nonlinear, see (Hals et al., 2002), (Babarit et al., 2006), (Falcao, 2007), (Sheng et al. 2015a; Sheng et al., 2015b). In addition, the end-stop or the power regulation in the PTO system (Babarit et al., 2012) introduces more nonlinear effects. For such nonlinear dynamic systems, a time domain analysis is normally needed.

One of the popular time domain methods is the one so-called hybrid frequency–time domain approach (Taghipour et al. 2008). This method consists two essential steps: the first step is the frequency domain analysis, in which the conventional boundary element method for potential flow can be used for assessing the hydrodynamic coefficients of the platforms, such as WAMIT[2] and ANSYS AQWA[3] and the recently available open source, Nemoh[4].

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[2] WAMIT Inc. (cited: 20/05/2014), http://wamit.com/
[3] ANSYS AQWA (cited: 20/05/2014), http://www.mecheng.osu.edu/documentation/Fluent14.5/145/AQWA/
[4] Nemoh (cited:20/05/2014), http://lheea.ec-nantes.fr/doku.php/emo/nemoh/start

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0029-8018/

Basically, these hydrodynamic coefficients are very frequency-dependent, and they cannot be used in the time domain analysis directly unless these parameters have a well-defined physical meaning, for example, a linear system in regular waves. When the dynamic system contains multiple frequencies, the frequency-dependent parameters lose their deterministic meaning. For this reason, the second step of the hybrid method is a transform of the hydrodynamic parameters from the frequency-domain to time domain, which has been formulated by (Cummins, 1962) and (Ogilvie, 1964). The advantages of the hybrid frequency–time domain equation may be the fast turnaround and the easiness to include the relevant nonlinear effects. The performance and/or power capture capacity of the wave energy converters in waves can be carried out if the time domain equations are solved.

In the Cummins' time-domain equation, the convolution integral (representing the memory effect in the fluid dynamics) is frequently found to be a problem in solving the dynamic equation. Principally, the convolution term can be carried out directly by integration, but it has a disadvantage for storing and renewing the history of the motions in every time step because the integration must be carried out back to a certain history if a good calculation of the memory effect is required. When many motion modes are considered, they are normally coupled each other, hence the number of the convolution terms increases very rapidly, proportional to the square of the motion mode number. Thus it may become a computational burden in the time domain analysis. Another disadvantage for the direct convolution integral is found in the real-time control system, when people find it is difficult to build the state-space equation for the dynamic system because of the existence of the convolution term.

To overcome the difficulty, many methods have been developed. Two most popular methods may be the Prony method, see (Duclos et al., 2001) and the state-space realisation method (Taghipour et al., 2008), (Perez and Fossen 2008; Perez and Fossen, 2009; Perez and Fossen, 2010) and (Duarte et al. 2013). Particularly, (Duarte et al., 2013) have developed an *SS_fitting* toolbox in Matlab for this purpose, which is now available for download[5]. Both methods are approximation methods, and the accuracy of the state-space method and the Prony method can be controlled by setting the order of the approximations. (Duclos et al., 2001) have shown the Prony's function of order of 3 has produced a very accurate approximation to a simple impulse response function. However, both approximation methods introduce additional equations to the dynamic system. When the more motion modes are coupled together, the additional equations will increase rapidly. The additional equations are not favourable in terms of the computational stability, especially when the dynamic system becomes difficult to solve, (for example, a very stiff system). In addition, the additional equations may add a significant computational time in solving the time-domain equation. (Kurniawan et al., 2011) have compared different methods in calculating the memory effect, namely the direct integration, the state-space fitting and the constant-coefficient model in terms of the computational time. It has been shown that the direct integral is the most accurate method, but slow, which is only dependent on the time step for integration. The state-space fitting gives a good approximation to the convolution term by introducing some additional differential equations to the dynamic system, and its accuracy is dependent on the order of the state-space. In some case, order 2 may give a good approximation. The constant coefficient method may be only used in some cases the quick approximation or in the system the radiation forces are small when compared to other forces.

[5] SS_Fitting (cited: 27/05/2014), http://wind.nrel.gov/designcodes/preprocessors/SS_Fitting/

In this research, a new method is developed for calculating the memory effect by extending the conventional Prony function method, see (Duclos et al., 2006). Unlike the developed approximation methods, the new method will not introduce any additional equation to the system, neither a requirement for storing and renewing the history of the motions in every time step. The new method in calculating the memory effect is simply a recursive calculation, which will be very beneficial in terms of the computational effort and the formulation of the state-space equation for a real-time control system.

The structure of the paper is as follows. In Section 2, the methodologies for studying the dynamics of floating structures in frequency domain and time domain are discussed; in Section 3 the approximation to the impulse function based on the Prony's method is presented. Section 4 deals with the new proposed method for calculating the radiation forces in time domain; in Section 5 the results and analysis will be made to show the accuracy efficiency of the method; and the conclusions will be given in Section 6.

2. Methodologies

2.1. Frequency-domain analysis

We consider a rigid floating structure which may experience 6-DOF motions. Based on the Second Newton's Law and appropriately rewriting the dynamic equation in frequency domain, it has a form as

$$\sum_{j=1}^{6M}\left[-\omega^2(m_{ij}+a_{ij})+i\omega b_{ij}+c_{ij}\right]\xi_i=f_i\ (i=1,\ldots,6M) \tag{1}$$

where a_{ij} and b_{ij} are the added mass and hydrodynamic damping coefficients, m_{ij} is the mass, c_{ij} the restoring coefficient, f_i the excitation, ω the circular frequency, ξ_i the complex amplitude of the motion, and M the number of the bodies.

A compact form of the frequency domain equation is,

$$\left\{-\omega^2[\mathbf{m}+\mathbf{a}(\omega)]+i\omega\mathbf{b}(\omega)+\mathbf{c}\right\}\boldsymbol{\xi}(\omega)=\mathbf{f}_{ex}(\omega) \tag{2}$$

The added mass, a_{ij}, and damping coefficient, b_{ij}, (both are real) can be assessed by the following formula:

$$a_{ij}-\frac{i}{\omega}b_{ij}=\rho\iint_{S_b}n_i\varphi_j dS\ \ (i,j=1,\ldots,6M) \tag{3}$$

where φ_j ($j=1,\ldots,6M$) is the potential of radiation due to the unit velocity of the structure, and S_b the wetted surface.

The excitation is calculated by

$$f_i=-i\omega\rho\iint_{S_b}\varphi^D n_i dS\ (i=1,\ldots,6M) \tag{4}$$

where φ^D is the potential of the diffracted waves (the incoming wave+scattered wave).

The hydrostatic restoring coefficients, c_{ij}, is also given in WAMIT based on the proper panels for the wetted surfaces (see Fig. 1). To illustrate the methodology, a simple oscillating body of a truncated circular cylinder, with a radius of 3 m and a draft of 1.5 m (Fig. 1 shows the panels for the wetted surface of the cylinder). The cylinder has a displacement of 42.41 m^3. In free floating state, the device may experience surge, heave and pitch motion under the wave excitation (heading waves). However, for wave energy conversion only heave is only taken for power conversion.

After solving the frequency domain equation, Eq. (1), the response amplitude operator X (i.e., the non-dimensional RAO for translational motions and the dimensional RAO for rotational