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TIME-DOMAIN ANALYSIS OF SUBSTRUCTURE OF A FLOATING OFFSHORE WIND TURBINE IN WAVES

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ABSTRACT

This paper aims to analyze the dynamic response of a floating offshore wind turbine (FOWT) in waves. Instead of modeling the incident random wave by the traditional wave spectrum and superposition theory, an impulse response function method was used to simulate the incident wave. The incident wave kinematics were evaluated by a convolution of the wave elevation at the original point and the impulse response function in the domain. To check the validity of current wave simulation method, the calculated incident wave velocities were compared with analytical solutions; they showed good agreement. The developed method was then used for the hydrodynamic analysis of the substructure of the FOWT. A direct time-domain method was used to calculate the wave-rigid body interaction problem. The proposed numerical scheme offers an effective way of modeling the incident wave by an arbitrary time series.

INTRODUCTION

Offshore wind energy is a promising alternative energy source to traditional energy. Fixed offshore wind turbines are widely operated in shallow water depth while floating wind turbines become increasingly popular in deep water. Designing an offshore wind turbine requires a fully coupled integrated analysis, incorporating the aerodynamic analysis, structural analysis and hydrodynamic analysis arising from a combination of environmental loadings. Wave loading, arising from the movement of seawater, is one of the most important aspects.

In recent efforts to develop simulation tools for FOWTs, designing and analyzing of a FOWT have benefited from offshore oil & gas industry. The types of floating structures, methods of analysis, etc are almost the same as offshore platforms. Many researchers have investigated the contributions from different nonlinearities of wave-structure interaction (e.g. Roald, et al, 2013; Karimirad, 2013). However, the inherent coupling effects and the complexity of FOWTs requires a re-examination of the traditional methods and types of structures. Plus, less attention has been paid on the calculation of velocity potential using an arbitrary time history. To this end, this paper introduced a method for calculating wave potential using an arbitrary incident wave profile. For the substructure of the FOWT, a direct time-domain method was used to calculate the wave-rigid body interaction problem. This direct time-domain method solved the diffracted and radiated wave together, as a scattered wave, instead of dividing the velocity potential into diffracted and radiated parts, unlike the traditional impulse response function method. Based on the linear wave-structure interaction theory, solving the integral equation with HOBEM, the velocity potential was updated at each time step. Based on the numerical method described above, the wave forces and motion responses of the floating body were calculated in the time domain. Results of current study, including wave forces, motion responses and wave profile around the floating body were compared to check the validity of current numerical modeling.

NOMENCLATURE

ω	Circular frequency
Φ^w	Incident potential
Φ^s	Scattered potential
Φ	Velocity potential
i	Complex value
ρ	Density of fluid
η	Wave elevation
A	Wave amplitude
B	Damping matrix
BVP	Boundary Value Problem
C	Restoring matrix
F	Wave force
FOWT	Floating Offshore Wind Turbine
g	Acceleration due to gravity
G	Green function
h	Impulse response function
H	Transfer function
HOBEM	Higher order boundary element method
K	Stiffness matrix
k	Wave number
M	Mass matrix
$\mathbf{n}$	Normal unit vector
p	Wave pressure
r	Radius between origin and calculated field
r_0	Radius between origin and inner damping layer
r_1	Radius between origin and outer damping layer
S_b	Body surface
S_f	Free surface
t	Time
X	Floating body motion response
x,y and z	Space coordinate
$\boldsymbol{\alpha}$	Floating body angular motion response
α_0, β_0 and λ	Damping coefficients
β	Wave direction
$\boldsymbol{\xi}$	Floating body transverse motion response

METHODOLOGY

Mathematical modeling for the incident wave

An impulse response function method was used to simulate the incident wave (King, 1986). Under linear system theory, the relationship between input x and output y for a system can be expressed as (Newland, 1978):

$$y(t)=\int_{-\infty}^{\infty} h(t)x(t-\tau)d\tau \tag{1}$$

Similarly, for the problem of wave propagation, wave potential and its derivatives in the field can be written as:

$$\Phi(t)=\int_{-\infty}^{\infty} h(t)\eta(t-t)dt \tag{2}$$

For linear wave theory, velocity potential and its derivatives have the following form:

$$\Phi(x,y,z,t)=\mathrm{Re}\{\frac{igA}{\omega}e^{kz}e^{-ik(x\cos\beta+y\sin\beta)}e^{i\omega t}\} \tag{3}$$

$$\frac{\partial\Phi(x,y,z,t)}{\partial t}=\mathrm{Re}\{-gA^{kz}e^{-ik(x\cos\beta+y\sin\beta)}e^{i\omega t}\} \tag{4}$$

and the corresponding wave profile

$$\eta=\mathrm{Re}\{Ae^{i\omega t}\} \tag{5}$$

where Re denotes the real part. The following parts will describe how the analytical solution of h is calculated.

Considering a sinusoidal wave with an amplitude of A (eq.5), the corresponding velocity potential is shown in eq 3. So the transfer function can be written as

$$H_{\frac{\partial\Phi}{\partial t}}(\omega,x,y,z)=-ge^{kz}e^{-ik(x\cos\beta+y\sin\beta)} \tag{6}$$

Using Inverse Fourier Transform, the analytical solution of the impulse response function was calculated from linear wave transfer function (eq 6). The analytical equation for impulse response function can be written as:

$$\begin{aligned}&h_{\frac{\partial\Phi}{\partial t}}(t,x,y,z)\\&=\int_{-\infty}^{\infty} H_{\frac{\partial\Phi}{\partial t}}(x,y,z)e^{i\omega t}d\omega\\&=-\frac{g}{2\pi}\int_{-\infty}^{\infty} e^{kz}e^{-ik(x\cos\beta+y\sin\beta)}e^{i\omega t}d\omega\end{aligned} \tag{7}$$

The final analytical form of the impulse response function h was given by King (1986):

$$\begin{aligned}&h_{\frac{\partial\Phi}{\partial t}}(t,x,y,z)\\&=-\frac{g}{2\pi}\frac{\sqrt{\pi g}}{\sqrt{-z+i(x\cos\beta+y\sin\beta)}}w\left(\frac{t\sqrt{g}}{2\sqrt{-z+i(x\cos\beta+y\sin\beta)}}\right)\end{aligned} \tag{8}$$

The derivation of $h_{\frac{\partial\Phi}{\partial x}}$ and $h_{\frac{\partial\Phi}{\partial z}}$ is the same as $h_{\frac{\partial\Phi}{\partial t}}$.

where w is the error function for complex values (Abramowitz and Stegun, 1964).

The incident wave kinematics and acceleration in the field were evaluated by a convolution of the wave elevation at the original point and the impulse response function in the domain (eq 2).

Mathematical and numerical modeling for wave-structure interaction problems

For wave-structure interaction problems, assuming non-viscous, non-rotational and incompressible flow, the velocity potential Φ satisfies the following equations in the fluid domain

$$\nabla^2\Phi=0 \tag{9}$$

Unlike the indirect time-domain method (Cummins, 1962), the direct time-domain method deals with the diffracted and radiated wave (Isaacson and Cheung, 1992)

$$\Phi=\Phi^w+\Phi^s \tag{10}$$

For the scattered wave potential, the following Laplace equation has to be satisfied

$$\nabla^2\Phi^s=0 \tag{11}$$

Figure 1 shows a sketch of calculation field and definition of coordinate. For linear wave-body interaction problems, the following boundary conditions have to be satisfied

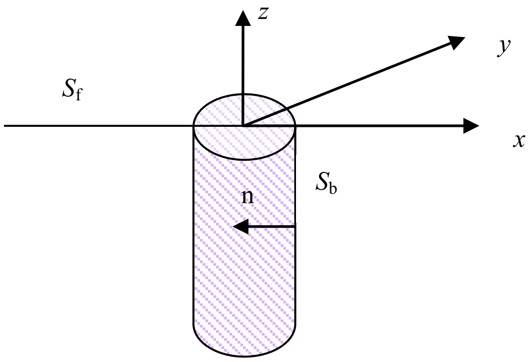

Figure 1 Definition of sketch

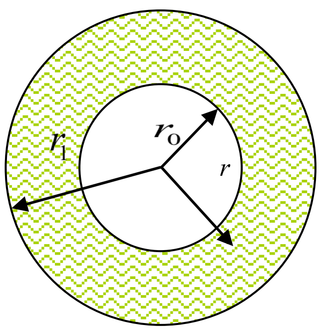

Figure 2 Sketch of damping layer

Free-surface condition

Using Taylor Series Expansion to first-order, the kinematic and dynamic conditions on the mean free surface can be written as (Ferrant, 1993):

$$\frac{\partial \eta^s}{\partial t}=\frac{\partial \Phi_s}{\partial \mathrm{z}}-\nu(r)\eta^s \tag{12}$$

$$\frac{\partial \Phi^s}{\partial \mathrm{t}}=-g\eta^s-\nu(r)\Phi^s \tag{13}$$

where

$$\nu(r)=\begin{cases}\alpha_0\omega\left(\dfrac{\mathrm{r}-r_0}{\beta_0\lambda}\right)^2 & r_0\le r\le r_1=r_0+\beta_0\lambda\\ 0 & r<r_0\end{cases}$$

Seabed condition

Assuming infinite water depth, velocity potential becomes zero with the increasing of water depth, so the following seabed condition has to be satisfied:

$$\lim_{z\to-\infty}\frac{\partial \Phi}{\partial \mathrm{z}}=0 \tag{14}$$

Body surface condition

The kinematic condition on the mean wetted body surface can be expressed as

$$\frac{\partial \Phi_s}{\partial \mathrm{n}}=-\frac{\partial \Phi_w}{\partial \mathrm{n}}+\left(\xi+\alpha\times X'\right)\cdot n \tag{15}$$

Radiation condition

An artificial damping layer has been added to avoid wave reflection, which has the same form as eqs 12 and 13. Figure 2 shows a sketch of damping layer.

The velocity potential in the field can be calculated by solving the following integral equation:

$$\alpha\Phi_s(x_0)=\iint_s\left[\frac{\partial G\left(x,x_0\right)}{\partial n}\Phi_s(x)-\frac{\partial \Phi_s(x)}{\partial n}G\left(x,x_0\right)\right]ds \tag{16}$$

where α denotes the solid angle and the Green function has the following form

$$G\left(x,x_0\right)=-\frac{1}{4\pi}\frac{1}{\sqrt{\left(x-x_o\right)^2+\left(y-y_o\right)^2+\left(z-z_o\right)^2}}$$

A higher-order boundary element method (Bai and Teng, 2001) was applied for solving the integral equation numerically:

$$\Phi(\xi,\varsigma)=\sum_{k=1}^{K}h^k(\xi,\varsigma)\Phi^k \tag{17}$$

$$\frac{\partial \Phi(\xi,\varsigma)}{\partial n}=\sum_{k=1}^{K}h^k(\xi,\varsigma)\left(\frac{\partial \Phi}{\partial n}\right)^k \tag{18}$$

Motion equation of the floating body was solved in the time domain directly:

$$\sum_{i=1}^{6}\left\{\left[M_i\right]\ddot{X}_i(t)+\left[B_i\right]\dot{X}_i(t)+\left[K_i+C_i\right]X_i(t)\right\}=F_i(t) \tag{19}$$

Velocity potential and wave profile were updated by a 4th-order Runge-Kutta method. Only first-order forces were considered in current study. Wave forces acting on a floating body was evaluated by Bernoulli equation:

$$p=-\rho(\frac{\partial \Phi}{\partial t}+\frac{1}{2}\nabla\Phi\cdot\nabla\Phi+gz) \tag{20}$$

VALIDATION OF THE IMPULSE RESPONSE FUNCTION METHOD

For validation purpose, a surface-piercing cylinder with 1m- draft and 1m- radius was selected (vertical center of gravity=-0.6). For validation purpose, here we choose the wave circular frequency=0.6 rad/s and wave amplitude=1m. To prevent the cylinder from drift away, an artificial stiffness matrix (10^9 kN/m) was added into motion equation during simulation. Figures 3.1-2.3 show a comparison of incident wave potential between present impulse response method and analytical solution. Figures 4.1-4.3 describe a comparison of wave forces. From the comparison we can see that very good agreement has been found between the two methods, offering a good preparation for the following case studies.

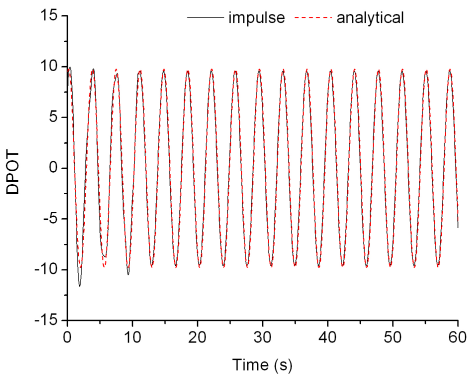

Figure 3.1 Comparison of velocity Φ_t

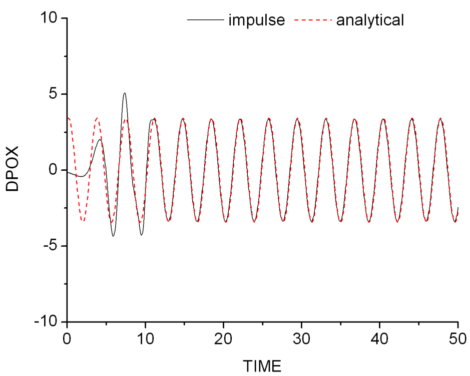

Figure 3.2 Comparison of velocity Φ_x

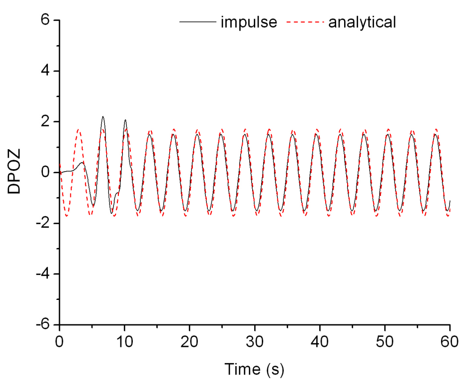

Figure 3.3 Comparison of velocity Φ_z

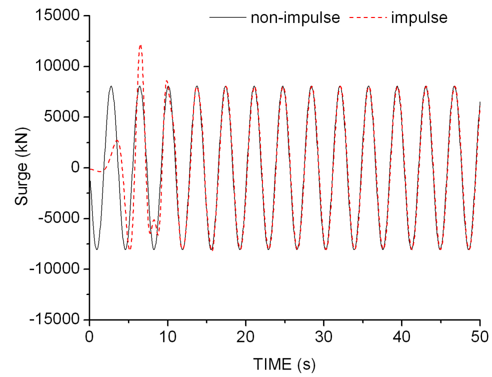

Figure 4.1 Comparison of wave forces, surge

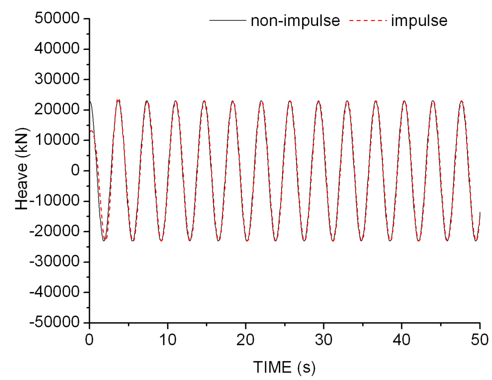

Figure 4.2 Comparison of wave forces, heave

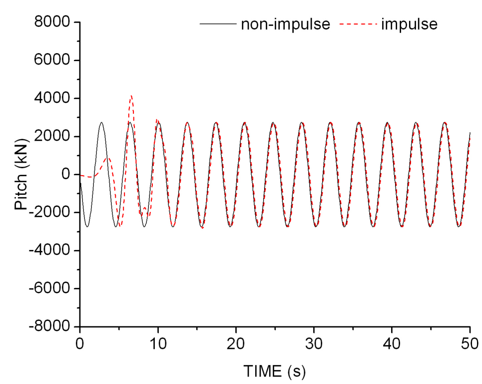

Figure 4.3 Comparison of wave forces, pitch

CASE STUDIES

A TLP-type floating structure mainly relies on mooring tethers to provide restoring forces. It has been considered as the most promising type of substructures for FOWTs. In this section, a baseline FOWT-NREL/MIT TLP has been selected for current case study, as an example of current developed program. Table 1 shows main properties of the TLP-type FOWT. Spoke was not included in present model. Mooring tether was simulated by linear spring and the spring stiffness was given by Christopher (2001). An arbitrary incident wave profile was shown in figure 5. Simulated wave forces and motion responses are show in figures 6.1-7.3.

Table 1 Main properties of NREL/MIT TLP

Parameters	Values
Platform radius (m)	18
Platform draft (m)	47.89
Displacement (m^2)	12179
Water depth (m)	200
Number of mooring lines	8

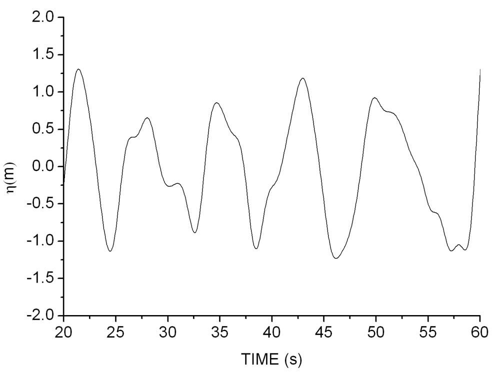

Figure 5 Incident wave profile

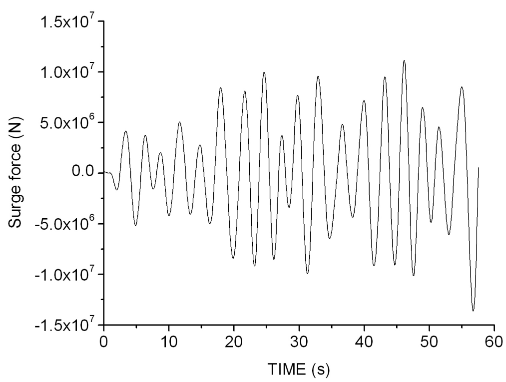

Figure 6.1 surge wave force

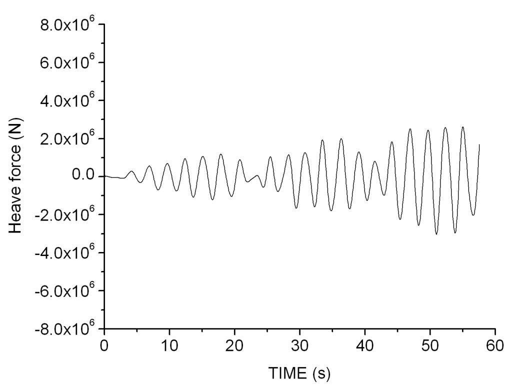

Figure 6.2 heave wave force

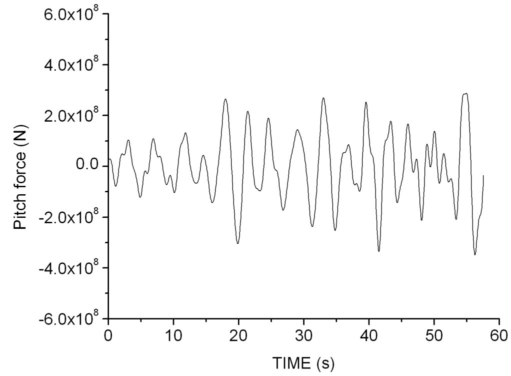

Figure 6.3 pitch wave force

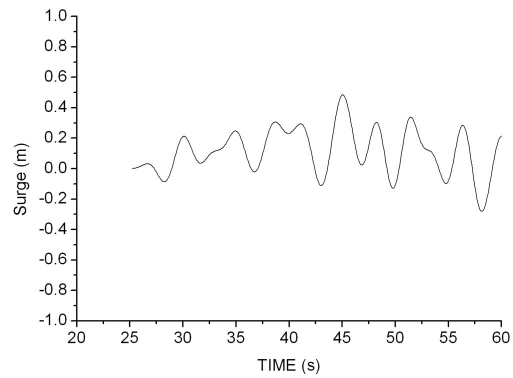

Figure 7.1 surge motion response

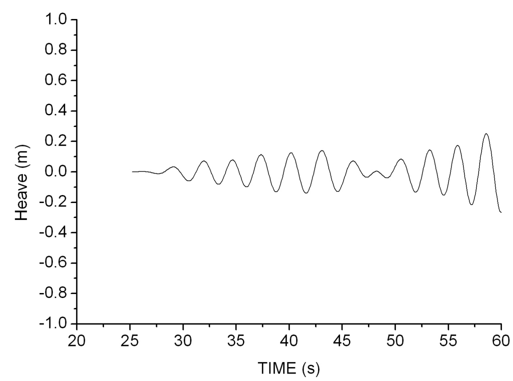

Figure 7.2 heave motion response

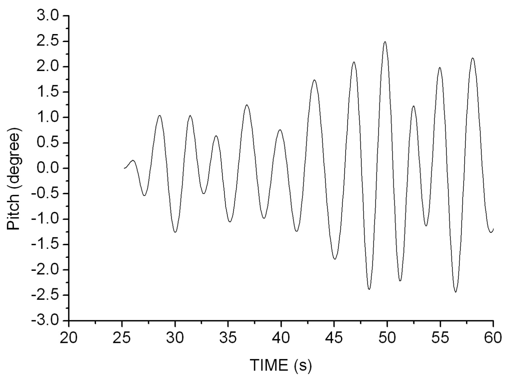

Figure 7.3 pitch motion response

CONCLUSIONS AND FURTHER STUDIES

A direct time-domain numerical code has been developed and its accuracy has been validated by a comparison between present results and analytical solutions. The developed numerical method represents an advance in simulating an incident wave by an arbitrary time history. This is an on-going research. Further study will include dynamic modeling of mooring line responses and aerodynamic loadings. Further validation of present method will be carried out by a comparison between numerical and experimental results. Guidance will be discussed about the suitability of different methods of analysis and advantages of different types of floating structures.

REFERENCES

1. Roald, L., Jonkman, J.,Robertson, A.,Chokani,N.,2013.The effect of second-order hydrodynamics on floating offshore wind turbines. Energy Procedia, 35, pp. 253-264.
2. Karimirad, M., 2013.Modeling aspects of a floating wind turbine for coupled wave-wind-induced dynamic analyses. Renewable Energy, 53, pp. 299-305.
3. Newland D. E. 1987, An Introduction to Random Vibrations and Spectral Analysis, Longman, London, in Chinese by the National Publishing Corporation, Peking.
4. Bradley K.K., 1987, Time-domain analysis of wave exciting forces on ships and bodies. Ann Arbor: The University of Michigan, Appendix A.
5. Abramowitz and Stegun., 1964, Handbook of Mathematical Functions. Courier Corporation.
6. Cummins W.E., 1962, The impulse response function and ship motions, DTMB Report 1661, Washington D.C.
7. Isaacson M. and Cheung K.F., 1992, Time-domain second-order wave diffraction in three dimension. J Waterway, Port, Coastal and Ocean Eng., ASCE, 118(5), 496~516.
8. Bai W. and Teng B., 2001, Second-order wave diffraction around 3-D bodies by a time-domain method, China Ocean Eng, 15(1), 73-85.
9. Ferrant P. ,1993, Three-dimensional unsteady wave-body interactions by a Rankine boundary element method. Ship Technology Research, 165-175.
10. Christopher Tracy. 2001, Parametric Design of Floating Wind Turbines.MIT Master Thesis.

