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Hydrodynamic analysis of wave impact forces and overturning moment on monopile foundations of offshore wind turbines

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Abstract

Renewable energy is that form of energy which is extracted from nature. Sunlight, wind, ocean waves etc. are the sources of renewable energy. The term renewable is used as this energy is naturally replenished. For this very reason, in recent times renewable energy has attracted a great deal of attention among academicians, industrialists and governments all over the world. Wind energy is at present the fastest growing renewable energy worldwide. Wind turbines are used to extract energy from wind. As offshore winds are less turbulent and they tend to flow at higher speeds than onshore winds, the offshore turbines produce more electricity. These turbines are supported by monopile foundations. As these structures are under constant wave action, the finding out of the wave impact loads and overturning moments on these structures is very important for proper design and installation of the same. In this paper the small amplitude wave theory is used to analyze the wave impact forces acting on a monopile foundation of an offshore wind turbine. Based on the aforesaid analysis a computer program has been developed in order to compute the drag force, the inertia force, the total force and total moment on a typical monopile foundation.

Keywords: *Monopile, Offshore Wind Turbine, Linear Wave Theory, Drag Force, Inertia Force.*

1. Introduction

Wind has been established in modern times as a source of renewable energy to generate electricity free from pollution through the use of wind turbines. A wind turbine (Fig. 1) can be compared to a fan operating in reverse. Rather than using electricity to produce wind, the turbine uses the wind to generate electricity. Wind flows over the airfoil-shaped blades of wind turbines and generates lift force which makes the turbine blades to turn. The blades are connected to a shaft that turns an electric generator to produce electricity. Wind turbines are used to harness the kinetic energy of the moving air over the oceans and convert it to electricity.

Fig. 1. Offshore wind turbines (Source: University of Cambridge)

In 2010 the wind power capacity increased more than 24% relative to 2009, with total global capacity nearing 198 GW by year's end. At least 52 countries increased their total existing capacity during 2010, and 83 countries now use wind power on a commercial basis. Over the period from end-2005 to end-2010, annual growth rates of cumulative wind power capacity averaged 27% [1].

Offshore winds are less turbulent and they tend to flow at higher speeds than onshore winds, thus allowing turbines to produce more electricity. Offshore wind turbines are usually supported by monopiles. Monopile structures provide the benefit of simplicity in fabrication and installation. It is a single column structure, consisting of a vertical circular cylinder. Such a structure is sometimes also used in offshore engineering to host some simple facilities such as a loading terminal and a light or radio instruments for navigation.

If one encounters a random offshore wind turbine there is a two-third probability that it will be supported by a monopile. The giant steel pipe is by far the most popular support structure in the world. At the dawn of 2011, 889 of the world's 1318 offshore wind turbines used monopiles for support.

However, the simple shape also calls for a large diameter of the monopile – ranging from 3.5 to 6.0 meters. As a result, the structure invites high hydrodynamic loads from the water waves – the water pushes and pulls the monopile and this affects the structure much more than for instance a jacket constructed out of smaller tubes. That is why the wave load analysis of these structures is very important.

A number of researchers have worked on wave impact loads on slender circular structure used for supporting the wind turbines. Goda [2] proposed a model for the impact force by considering the breaking wave as a vertical wall of water hitting the cylinder with wave celerity. Wienke *et al.* [3] developed theoretical formulae for the load due to breaking wave impact on slender piles based on large scale experiments. The load distribution in time and space was given by the proposed theoretical three dimensional impact model. The formulae were applied to calculate the impact force on a support tower of a wind turbine subjected to breaking wave. Corte and Grilli [4] studied the impact on cylindrical piles of extreme waves (freak waves), generated by directional wave focusing. Waves were numerically modeled based on a boundary element discretization of fully nonlinear potential flow equations with free surface evolution. Higher-order boundary elements were used for the spatial discretization, and a higher-order time integration scheme based on the Taylor series expansion was applied. Finally, the full loading on a cylindrical tower structure, due to a freak wave, was determined. Some other contributory researchers in this field are Ferro and Mansour [5], Arai and Matsunaga [6], Basco and Niedzwecki [7], Matthies *et al.* [8] etc.

In this paper the small amplitude wave theory is used to analyze the wave impact forces acting on a monopile foundation of an offshore wind turbine. Based on the aforesaid analysis a computer program has been developed in order to compute the drag force, the inertia force and the total force on a typical monopile foundation. The computational results are plotted and physically interpreted.

2. Mathematical formulation

This section presents a theoretical analysis of the wave forces acting on a monopile foundation of an offshore wind turbine. The analysis is based on the linear wave theory.

Fig. 2 shows a model of a cylinder, in this case, a monopile, on which incident wave is impinging. In this Fig. the mean water level represents *X* axis and the vertical axis from mean water level is *Z*. The wave height is *H*, instantaneous wave height is η, wave length *L* and depth of water is *d*. The diameter of the cylinder is *D*.
The total in-line wave load for unit height of monopile at a depth $z + d$ for an accelerated water environment where the cylinder is held stationary is given by

$$F_T = \frac{1}{2}\rho C_D D U|U| + \rho C_m A\dot{U} + \rho A\dot{U} \qquad (1)$$

where F_T is the total force per unit length of the cylinder, ρ the fluid density, C_D the drag coefficient, C_m the hydrodynamic mass coefficient, U is horizontal wave induced velocity of water and $\dot{U}$ is the horizontal wave induced acceleration of water and A is the cross sectional area of the cylinder [9].

On the right hand side of Equation number (1), the first term represents drag force, the second term the hydrodynamic mass force and the third term the Froude-Krylov force. The Froude-Krylov force is caused by the acceleration of the fluid in the immediate surroundings of the body.
equation number (1) can be written in the following form:

$$F_T = \frac{1}{2}\rho C_D D U|U| + \rho(C_m + 1)A\dot{U} \qquad (2)$$

Defining a new coefficient, C_M, as

$$C_M = C_m + 1 \qquad (3)$$

Equation number (2) becomes

$$F_T = \frac{1}{2}\rho C_D DU|U| + \rho C_M A\dot{U} \tag{4}$$

Equation number (4) is known as the Morison equation [10]. The new force term, $\rho C_M A\dot{U}$, is called the inertia force and the new coefficient C_M is called the inertia coefficient.

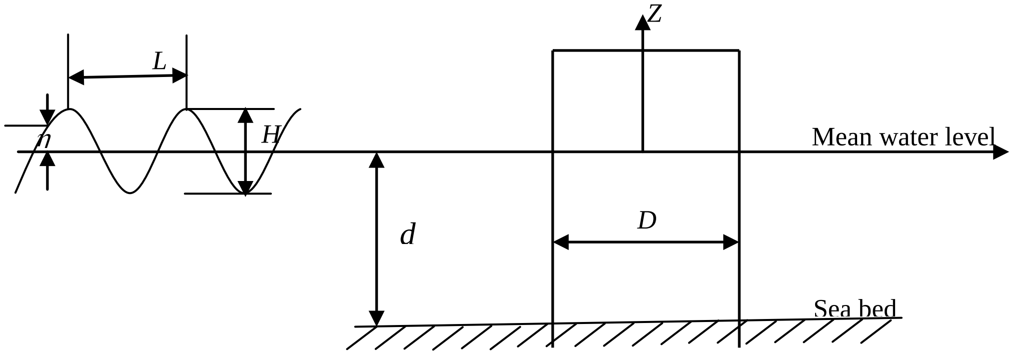

Fig. 2. Definition sketch of a circular cylinder on which incident wave is impinging.

The drag and inertia coefficients are in general functions of the Reynolds number, the Keulegan-Carpenter number and the relative roughness. The coefficients also depend on the cross-sectional shape of the structure and of the orientation of the body.

The Reynolds number (*Re*) and the Keulegan-Carpentar number (*KC*) are calculated using the following expressions:

$$\left.\begin{array}{l} Re = \dfrac{U_{\max} D}{\nu} \quad \text{and} \\ KC = \dfrac{U_{\max} T}{D} \end{array}\right\} \tag{5}$$

where $U_{\max}$ is the maximum horizontal velocity of water at still water level, ν is the kinematic viscosity of seawater, and T is the period of the waves. The drag coefficient C_{DS} for steady-state flow can be used as a basis for calculation of C_D and C_M [11].

The potential function for a small amplitude progressive wave is

$$\phi = \frac{HC}{2}\frac{\cosh m(z+d)}{\sinh md}\sin(mx - nt) \tag{6}$$

where C is the wave celerity, m is the wave number and n is the wave frequency [12].

$$\left.\begin{array}{l} C = \dfrac{L}{T} \\ m = \dfrac{2\pi}{L} \\ \text{and} \\ n = \dfrac{2\pi}{T} \end{array}\right\} \tag{7}$$

The well known expression for wave celerity is

$$C^2 = \frac{g}{m}\tanh md \tag{8}$$

where g is the gravitational acceleration.

From equation numbers (7) and (8), we obtain

$$L = \frac{gT^2}{2\pi}\tanh\frac{2\pi d}{L} \tag{9}$$

The horizontal velocity of the water particle is

$$U = \frac{\partial\phi}{\partial x} = \frac{HCm}{2}\frac{\cosh m(z+d)}{\sinh md}\cos(mx - nt) \tag{10}$$

From equation numbers (7) and (10), we get

$$U = \frac{\pi H}{T}\frac{\cosh m(z+d)}{\sinh md}\cos(mx - nt) \tag{11}$$

The horizontal acceleration of the water particle is

$$\dot{U} = \frac{\partial U}{\partial t} = \frac{2\pi^2 H}{T^2} \frac{\cosh m(z+d)}{\sinh md} \sin(mx - nt) \tag{12}$$

The term (*mx*-*nt*) in equation numbers (11) and (12) is called the phase angle.
Let

$$mx - nt = \theta \tag{13}$$

Thus equation (11) and equation (12) can be written as

$$U = \frac{\pi H}{T} \frac{\cosh m(z+d)}{\sinh md} \cos\theta \tag{14}$$

and

$$\dot{U} = \frac{2\pi^2 H}{T^2} \frac{\cosh m(z+d)}{\sinh md} \sin\theta \tag{15}$$

From equation number (4), the expression of drag force can be written as

$$F_D = \frac{1}{2} \rho C_D D U |U| \tag{16}$$

Combining equations (14) and (16), we get

$$F_D = \frac{1}{2} \rho C_D D \left(\frac{\pi H}{T} \frac{\cosh m(z+d)}{\sinh md} \cos\theta \right) \left| \frac{\pi H}{T} \frac{\cosh m(z+d)}{\sinh md} \cos\theta \right| \tag{17}$$

From equation number (4), the inertia force can be expressed as

$$F_I = \rho C_M A \dot{U} \tag{18}$$

Combining equation numbers (15) and (18), we get

$$F_I = \rho C_M A \left(\frac{2\pi^2 H}{T^2} \frac{\cosh m(z+d)}{\sinh md} \sin\theta \right) \tag{19}$$

Let the submerged length of the monopile be *s*.

$$\therefore\ s = z + d \tag{20}$$

The total horizontal force over the submerged length of the monopile foundation F_{ST} can be found by integration of Morison's equation for values of *s* from 0 to the instantaneous wave height from the seabed ($d+\eta$).

$$F_{ST} = \int_0^{d+\eta} \frac{1}{2} \rho C_D D U |U| \, ds + \int_0^{d+\eta} \rho C_M A \dot{U} \, ds \tag{21}$$

The instantaneous wave height can be expressed as

$$\eta = \frac{H}{2} \cos(mx - nt) \tag{22}$$

For simplicity, let the monopile be located at $x = 0$. Then we get

$$\left.\begin{aligned} &\theta = mx - nt = -nt \\ &\eta = \frac{H}{2} \cos nt \\ &U = \frac{\pi H}{T} \frac{\cosh m(z+d)}{\sinh md} \cos nt \\ &\text{and} \\ &\dot{U} = -\frac{2\pi^2 H}{T^2} \frac{\cosh m(z+d)}{\sinh md} \sin nt \end{aligned}\right\} \tag{23}$$

Combining equation numbers (20), (21) and (23), we get

$$F_{ST} = \int_0^{d+\eta} \frac{1}{2} \rho C_D D \left(\frac{\pi H}{T} \right)^2 \cos nt |\cos nt| \frac{\cosh^2 ms}{\sinh^2 md} ds - \int_0^{d+\eta} \rho C_M A \left(\frac{2\pi^2 H}{T^2} \right) \sin nt \frac{\cosh ms}{\sinh md} ds \tag{24}$$

Using the well known relationship $n^2 = mg \tanh md$ and integrating equation (24), we get

$$F_{ST} = \frac{1}{8}\rho C_D D H^2 gmd \frac{\cos nt\left|\cos nt\right|}{\sinh 2md}\left[\frac{1}{2md}\sinh 2md\left(1+\frac{\eta}{d}\right)+\left(1+\frac{\eta}{d}\right)\right] - \frac{1}{8}\rho C_M \pi D^2 gH \frac{\sin nt}{\cosh md}\left[\sinh md\left(1+\frac{\eta}{d}\right)\right] \quad (25)$$

The total moment about the ocean floor is derived as

$$M_T = \int_0^{d+\eta} s\, dF_T \quad (26)$$

and if the integration is carried out,

$$M_T = \frac{1}{8}\rho C_D D H^2 dgmd \frac{\cos nt\left|\cos nt\right|}{\sinh 2md}\left[\frac{\left(1+\frac{\eta}{d}\right)^2}{2}+\frac{\left(1+\frac{\eta}{d}\right)}{2md}\sinh 2md\left(1+\frac{\eta}{d}\right)+\frac{1}{(2md)^2}\left(1-\cosh 2md\left(1+\frac{\eta}{d}\right)\right)\right] - \frac{1}{8}\rho C_M \pi D^2 Hdg \frac{\sin nt}{\cosh md}\left[\left(1+\frac{\eta}{d}\right)\sinh md\left(1+\frac{\eta}{d}\right)+\frac{1}{md}\left(1-\cosh md\left(1+\frac{\eta}{d}\right)\right)\right] \quad (27)$$

Equation numbers (25) and (27) are valid for both deep and shallow water waves.

3. Results and discussion

In order to demonstrate the actual calculation procedure, a typical monopile foundation of 5 m diameter (D) at a location of 25 m water depth (d) is chosen. The following metocean data is considered for the calculation.

Table 1. Metocean data for calculating wave load on monopile foundation

Parameter	Values
Wave height, H (m)	8.0
Wave period, T (sec)	9.4
Mass density of sea water, ρ (kg/m^3)	1025

The wave length L is calculated as 119.4 m by trial and error method using Equation (12). We get the value of C_{DS} as 0.65 for smooth steel pipe.

Fig. 3 (a) shows the variation of drag force (F_D), inertia force (F_I) and total force (F_T) with the phase angle (θ). Equation numbers (4), (17) and (19) are used to plot this figure. It is observed that the variation of the drag force is not a sinusoidal one. The maximum drag force (18447.43 N) occurs at 0 and 360 degrees and minimum force (-18447.43 N) at 180 and 540 degrees. It is interesting to note that the variation of inertia force is sinusoidal. The maximum and minimum values are ± 91199.09 N. The maximum inertia force occurs at θ equal to 90 and 450 degrees whereas the minimum inertia force occurs at θ equal to 270 and 630 degrees. It is observed that the variation of the total force is represented by a curve which is nearly sinusoidal. This can be easily understood from the fact that the inertia force is much greater than the drag force and there is a phase difference of 90 degrees between these two components of the total wave force.

Equation number (25) is used for plotting Fig. 3(b). The total horizontal force over the submerged length of the monopile foundation (F_{ST}) and its two components (drag force and inertia force) are varied with non-dimensional time (t/T). It is to be noted that the inertia force component is negative in equation number (25). It is seen that the maximum total horizontal force over the submerged length of the monopile foundation occurs at t/T = 0.8. The inertia force is much greater than the drag force and there is a phase difference of 90 degrees between these two components of the total wave force.

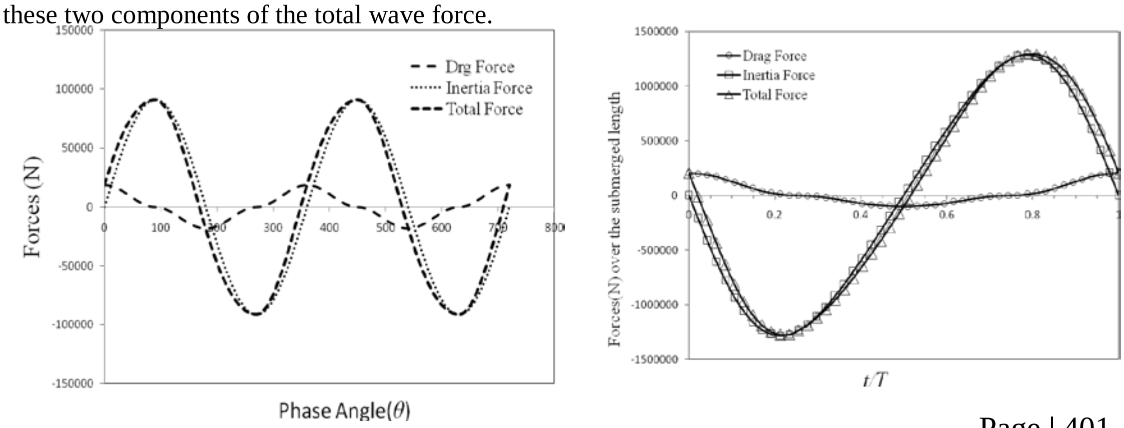

Fig. 3. Variation of forces with phase angle (θ) and non-dimensional time (t/T)

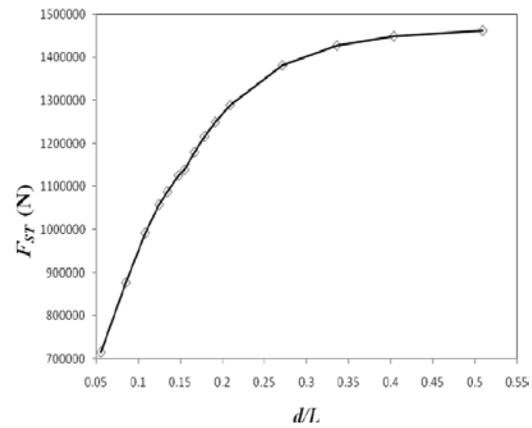

Fig. 4. Variation of total horizontal force (F_{ST}) with relative depth (*d/L*)

The relative depth is defined as the ratio of depth of water to the wave length (*d/L*). Fig. 4 shows the variation of the total horizontal force (F_{ST}) with relative depth. It is observed that F_{ST} increases almost linearly up to d/L = 0.3 and then the rate of increase is somewhat lower.

4. Conclusions

This paper presents a hydrodynamic analysis of the wave impact forces on the monopile foundation of an offshore wind turbine. The following conclusions can be drawn from the present work:

1. The linear wave theory is used to calculate the drag force (F_D), inertia force (F_I) and total force (F_T) acting on a monopile foundation.
2. The inertia force (F_I) component is much larger than the drag force component (F_D).
3. The variation of the drag force (F_D) with the phase angle (θ) is not sinusoidal whereas the variation of the inertia force (F_I) with the phase angle (θ) is sinusoidal.
4. The variation of the total force (F_T) with the phase angle (θ) is nearly sinusoidal.
5. The total horizontal force over the submerged length of the monopile foundation is maximum when inertia force component is maximum.
6. The relative depth (*d/L*) has a great influence on the magnitude of the total horizontal force (F_{ST}). It is observed that (F_{ST}) increases almost linearly up to d/L = 0.3 and then the rate of increase is somewhat low.

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