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Comparison of hydrodynamic loading models for vertical cylinders in nonlinear waves

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Abstract

This paper introduces a comparison study between various hydrodynamic loading models in highly nonlinear waves and discusses its first phase – comparing Morison equation and Rainey corrections on a fixed cylinder in regular steep waves. In this study both of these two models showed similar results when compared against experimental data. Morison equation is found to capture the amplitude of the loading sufficiently well. However, neither model was able to capture higher-order loading components which are apparent in very steep waves and are associated with ringing. The main conclusion of this work is the identification of the need of a more appropriate loading model.

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Keywords: Monopile-supported offshore wind turbines; nonlinear wave loads; hydrodynamic loading models

Nomenclature

C_d	drag coefficient
C_m	inertia coefficient
η	instantaneous free surface elevation
R	cylinder radius
ρ	water density

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v_x	horizontal water particle velocity
$\dot{v}_x$	horizontal water particle acceleration
v_z	vertical water particle velocity

1. Introduction

In the times of constantly increasing energy demand and climate change, the large-scale offshore wind turbines provide a clean and renewable energy source, generating a substantial amount of electricity per turbine [1]. The large size of the turbine also imposes higher costs for the technology, support structure being one of the most expensive parts. More accurate modelling of the wave loads could contribute to the reduction of this cost.

The environmental conditions where offshore wind turbines are placed can be very rough, including steep waves where wave nonlinearities become important. Wave kinematics are commonly modelled linearized or weakly nonlinear, but it has been shown that the nonlinearities can significantly affect the extreme and fatigue loads on the structure [2]–[4] and cause highly nonlinear resonant response, such as ringing [5]–[7]. Monopile-supported offshore wind turbines have been found prone to such nonlinear effect, yet they are omitted if linear wave kinematics are used.

The most regularly used hydrodynamic loading model for monopile-supported offshore wind turbines is Morison equation [8]. This semi-empirical formula consists of inertia and drag terms, the coefficients for which have to be calibrated by experimental data or available guidelines. Well adjusted, Morison equation normally is adequate to determine the linear part of the loading. However, the dangerous nonlinear effects on the structure are caused by higher harmonics in the loading, and that is where the suitability of Morison equation has been doubted. Chaplin et al. (1997) [9] conducted a study on ringing response of a cylinder in steep focused waves, and stated that Morison equation under-predicted peak forces and moments on a fixed cylinder. Ma et al. (2009) [10] also conducted an experimental study with focused waves finding that Morison formulation had sufficient agreement for the first harmonic of loading, but not the higher ones. Paulsen et al. (2014) [11] modelled fully nonlinear wave kinematics to study wave forcing at finite depth and have noted that the third-harmonics modelled by Morison equation deviate at shallower depths.

More accurate load determination for monopile-supported offshore wind turbines in highly nonlinear situations therefore seems to require more sophisticated models. Most well-established of such are slender-body theory by Rainey [12,13] which suggests corrections to Morison's inertia term by consideration of axial divergence, surface intersection and surface distortion components; and also perturbation theories, such as Malenica and Molin [14] and FNV theory [15], which directly take into account the third order loads, associated with the nonlinear resonant phenomena.

This paper presents the first stage of comparison between different hydrodynamic loading models on surface piercing vertical cylinders. This phase compares the loading by Morison equation and Rainey corrections on fixed rigid cylinder in steep regular fully nonlinear waves, as illustrated in Figure 1.

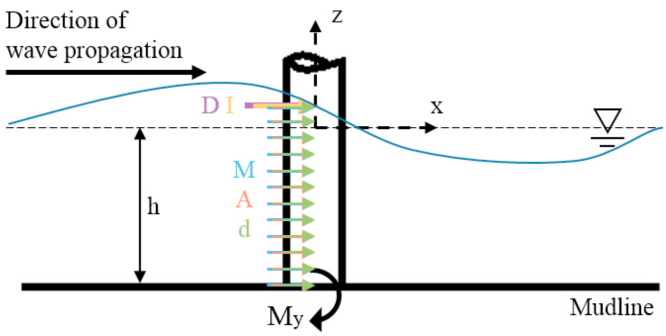

Fig. 1. Schematic representation of the analysed truncated cylinder and associated coordinate systems.

2. Wave kinematics and loading models

2.1. Fully nonlinear wave kinematic solver

The fully nonlinear gravity water waves are modelled by a potential flow-based higher-order boundary element method (HOBEM) model [16-18]. Laplace equation is solved within the domain bounded by impermeable bottom, periodicity on vertical walls for regular waves, and free water surface. The free surface is solved for in the steady quadratic HOBEM and stepped in time by 4th order Runge-Kutta algorithm.

The solver is initialized and validated with the Rienecker-Fenton [19] theory for waves of high steepness. To prevent numerical instabilities, potential continuity in corners by Grilli et al. (1990) [20] and 5-point smoothing introduced by Louguet-Higgins and Cokelet (1976) [21] are employed in the numerical solver.

2.2. Hydrodynamic loading models

The first hydrodynamic loading model, presented in Equation 1, is Morison equation [8], which is most universally used because of its simplicity. It consists of an inertia term (M), corresponding to horizontal acceleration of the flow, and a quadratic drag term (d), which corresponds to horizontal velocity while keeping its sign. Both of these terms are integrated along the length of the cylinder from the bottom up to the instantaneous water surface and are 90° out of phase with each other. For further simplicity it is common to neglect either of the terms if the cylinder belongs to inertia or drag dominated region. The Keulegan-Carpenter number in this study indicates that the analyzed cylinders fall between the two regions, therefore full quadratic Morison equation is used.

$$F_{Mor} = \underbrace{\int_{-h}^{\eta} C_m \rho \pi R^2 \dot{v}_x dz}_{M} + \underbrace{\int_{-h}^{\eta} C_d \rho R |v_x| v_x dz}_{d} \tag{1}$$

Slender-body theory by Rainey [12,13], also known as Rainey corrections, proposes to separate the Morison inertia term (M) and apply potential flow corrections, listed in Table 1, to it. Morison drag component (d) is added after the corrections for comparison.

Table 1. Slender-body theory components and their formulations, following [9].

Axial divergence force	Surface intersection force	Surface distortion force
Integrated along the length of the cylinder	Point load applied at the intersection with the free surface	Point load applied at the intersection with the free surface
$A = \int_{-h}^{\eta} \rho \pi R^2 (\partial v_z / \partial z) v_x dz$ (2)	$I = -(\rho \pi R^2 / 2) v_x^2 \, \partial \eta / \partial x$ (3)	$D = (7 \rho \pi R^2 / 2g) v_x^2 \dot{v}_x$ (4)

3. Results and discussion

3.1. Comparison with Chaplin et al. (1997)

The first step in the comparison was numerically recreating the study by Chaplin et al. (1997) [9]. They conducted experiments on surface-piercing fixed and pivoted cylinders in focused waves, and compared them to base bending moments computed by Morison equation and by Rainey corrections. Wave kinematics were modelled in two ways: by crest-fitting technique as unsteady waves, and by regular waves of periods and wave heights corresponding to the measured. In this study wave kinematics were modelled by the second technique – using equivalent regular waves. Comparison of bending moments on a fixed cylinder of 100 mm diameter on waves of steepness kA = 0.299 are illustrated in Figure 2.

It is noted that the bending moments modelled in the current study recreate the ones computed by Chaplin et al. (1997) quite well (refer to Figure 6b in [9] for comparison). The original figure in [9] contains only the experimental values and configurations of 'M', 'M+A' and 'M+A+I' for the regular wave kinematics case, although from the current Figure 2 it appears that the addition of the surface distortion component (D) and the drag force (d) matches the experimental result, especially the peak, more closely. However, Chaplin et al. (1997) [9] showed that when the moments were computed with unsteady waves, inclusion of these two components led to a significant over-prediction of the peak moment.

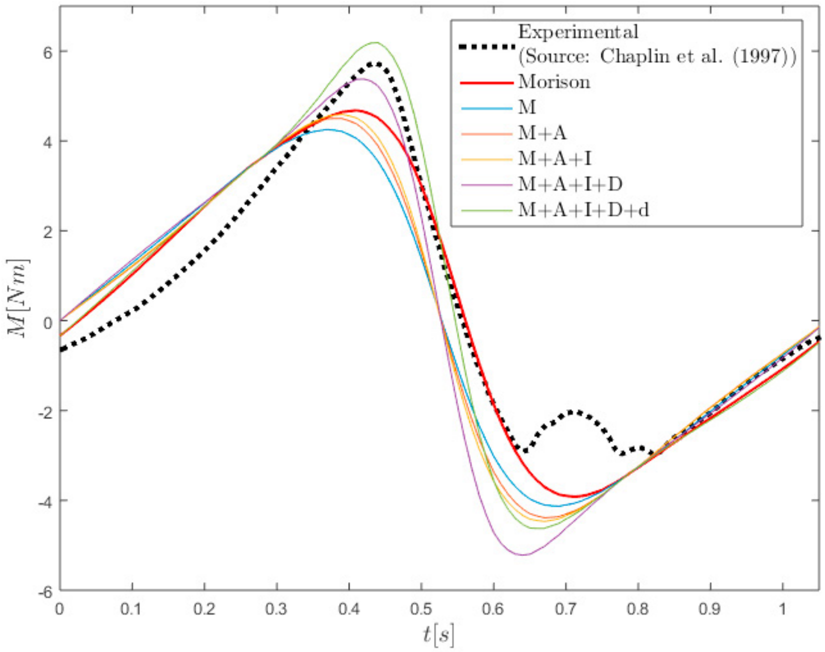

Fig. 2. Comparison of bending moments on a fixed cylinder of 100 mm diameter in waves of steepness kA = 0.299.
Moments are measured by Chaplin et al. (1997) and computed with Morison equation and slender-body term corrections to it.

The moments based on Morison equation were also excluded from the original figure in the regular wave case (Figure 6b in [9]), yet in this study it matches the experimental curve closer than the slender-body corrections. However, it must be noted that the experimental values were obtained with focused waves. On the contrary to the distortion and drag components, the comparison for the moments modelled with wave kinematics from crest-fitting technique in the original study (Figure 6a in [9]) did not include full Morison equation. Since the drag component caused a significant over-prediction of the peak, it may be expected that full Morison equation would show similar behavior, but the comparison in this case is not of sufficient significance to draw conclusions. Further study is needed on either modelling the moments from focused wave kinematics or a comparison to experiments with regular waves. Chaplin et al. (1997) [9] excluded their experiments on regular waves because the response of the cylinder lasted much longer than the wave period and focused waves allowed for a better observation. Therefore a comparison with the experiments of Stansberg (1997) [22] were conducted next.

Finally, neither of the models was able to capture the secondary loading (t ≈ 0.65–0.85 s), associated with ringing, indicating that a more sophisticated hydrodynamic loading model might be needed.

3.2. Comparison with Stansberg (1997)

Stansberg (1997) [22] investigated ringing loads on fixed cylinders in regular and irregular waves. Figure 3 shows the experimental results on a cylinder of radius R = 100 mm in regular waves of amplitude Aw = 0.162 m, period T = 1.52 s, and steepness kA = 0.282. The forces are normalized by the square radius of the cylinder. The normalized forces, computed by Morison equation and Rainey corrections are displaced for comparison.

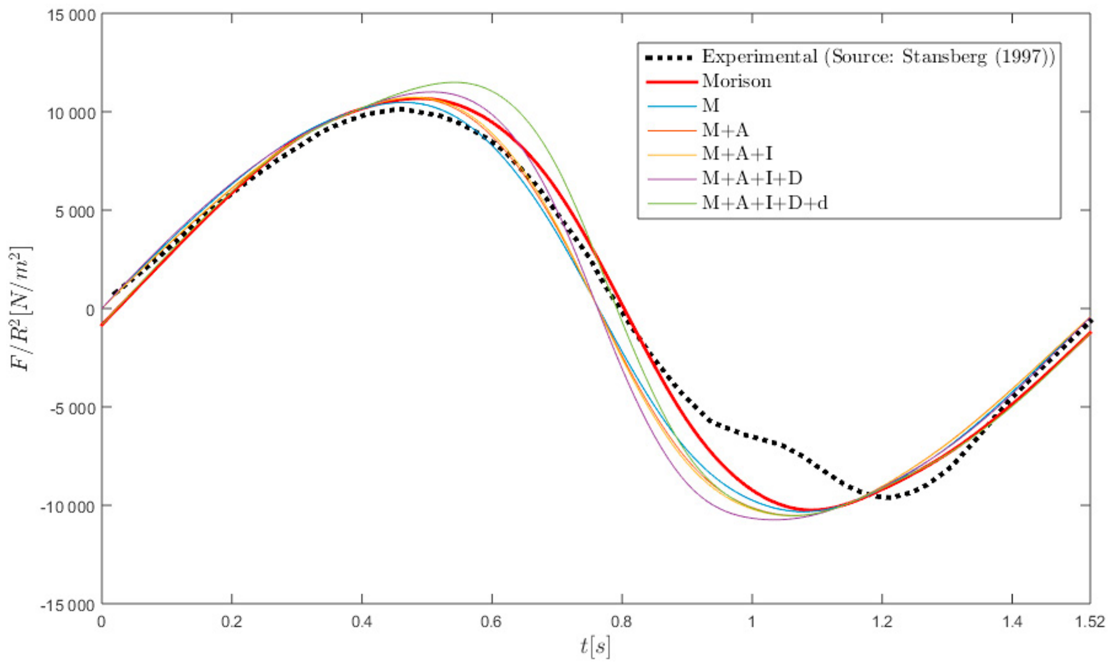

Fig. 3. Comparison of normalized horizontal forces (F/R^2) on a fixed cylinder of 100 mm radius in regular waves of T = 1.52 s, Aw = 0.162 m, kA = 0.282. Forces are measured by Stansberg (1997) and computed with Morison equation and slender-body term corrections to it.

It is seen that the peak force was overestimated by all of the models, the largest deviation being added by the correction for surface distortion. The most important discrepancy, however, occurs at the evident nonlinearity in the through ($t \approx 0.9$–1.2 s). This was explained as higher-order loading content, which was identified by the use of high-pass filter, is most evident in the steepest waves and is associated with ringing [22]. None of the presently analyzed hydrodynamic loading models captured this additional loading content. Stansberg (1997) [22] states that this loading is of third order or higher, while Morison's equation consists of linear inertia term and quadratic drag, whereas in Rainey corrections the slender-body terms bring the Morison inertia term up to the accuracy of the second order in Stokes expansion, but neither option includes the third-order terms. The omission of higher-order terms by hydrodynamic loading models up to second order is confirmed also in the OC5 project [7,23], where the participants used Morison equation and 1st or 2nd order potential flow theory, and none were able to catch this additional loading seen experimentally. In contrast, Stansberg (1997) [22] for the analytic comparison employed FNV theory which considers the higher-order terms. The next step of this ongoing study is to add a perturbation theory, such as FNV, to the comparison.

4. Concluding remarks

A study on fixed surface-piercing cylinders in very steep regular waves was conducted, comparing Morison equation and Rainey corrections to it. Comparisons were carried out with previous experimental studies of Chaplin et al. (1997) [9] and Stansberg (1997) [22], and both of the analyzed hydrodynamic loading models showed similar results. Morison equation was capable of capturing the magnitudes of the forces and moments, while Rainey corrections led to a slight deviation of the response in the analyzed cases. However, neither of the models was able to catch the secondary loading, occurring in highly nonlinear waves and associated with ringing loading, signifying that more sophisticated hydrodynamic loading models are required wanting to investigate nonlinear loading.

Next phases of this ongoing research will include a perturbation theory, such as FNV [15] into the comparison, consideration of the motion of the body by conducting a study on a pivoted cylinder, and then a full dynamic response of an operating offshore wind turbine by coupling with a hydro-aero-servo-elastic solver. Results of the study are expected to provide considerations for improved hydrodynamic loading models for vertical cylinders in strongly nonlinear waves with the application to monopile-supported offshore wind turbines.

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