Ocean Engineering 38 (2011) 2000–2014

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Experimental and numerical investigation of the slowly varying wave exciting drift forces on a restrained body in bi-chromatic waves

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ARTICLE INFO

Article history:
Received 6 August 2010
Accepted 10 September 2011
Editor-in-Chief: A.I. Incecik
Available online 28 October 2011

Keywords:
Wave exciting forces
Slowly varying forces
Second order forces
Bi-chromatic waves
Difference frequency forces
Water depth effects
Experimental work
Potential flow methods

ABSTRACT

The paper presents an experimental and numerical investigation of the first order and slowly varying wave exciting forces on a body of simple geometry which is restrained from moving. Both monochromatic waves and three sets of bi-chromatic waves corresponding to three difference frequencies were tested. The depth effects on the second order forces are assessed by repeating the wave conditions for deep water, intermediate water depth and shallow water. The wave exciting mean drift forces and second order slowly varying forces were successfully measured and identified. However, since the magnitude of these forces is small compared to the global forces measured, there is some dispersion in the second order results.

The experimental data is compared with three state of the art numerical methods which are able to compute the first and second order wave exciting forces. Two of the methods use Green's function panel methods (Wamit and HydroStar) and the third is based on an analytical solution (Diffrac-R). All methods compute the full second order solution, including the effects related to the quadratic interactions of first order quantities and to the second order diffraction potentials.

1. Introduction

A floating or fixed marine structure subjected to multi-frequency incident wave field will experience second order wave exciting forces. These are related to the interactions between pairs of harmonic wave components composing the wave field. Within a frequency domain approach, these forces can be decomposed into three components namely: a steady force, a difference frequency component and a sum frequency component. The first represents a mean value which is frequency dependent, but time independent. The other components change harmonically in time, one with the sum frequency of the pair of harmonic waves and the other with the difference frequency.

Sum and difference frequency effects are important for different problems. Sum frequency second order forces occur at relatively high frequencies and they may excite the natural periods of floating structures moored with taut cables, like the tension leg platforms. In this case the natural period of the vertical motions is small, the associated wave damping is low, therefore the sum frequency forces may induce resonant vertical motions which results on undesirable dynamic effects (springing loads). These effects have been identified at the full scale (e.g. Standing et al., 1993) and confirmed at the model scale (see for example Herfjord and Nielson, 1986).

In the case of the difference frequency second order forces, they result on the slowly varying wave drift excitation in irregular seas, which are important, for example, for floating moored structures. For many floating structures the mooring system is compliant with the first order wave exciting forces, since the natural period of the moored floater is large compared to the wave period. However the slowly varying drift forces have longer periods and therefore they may excite the floater and mooring system at their natural frequency resulting in large horizontal motions of the floater and tensions on the mooring lines (see for example Pinkster, 1976, 1980; Emmerhoff and Sclavounos, 1996). Semi-submersibles may also be excited in the pitch motion by slow drift forces because they have a long natural period of pitch. Stansberg (2007) investigated experimentally the slow drift pitch motions of a semi-submersible.

Many offshore floating systems use dynamic positioning (DP) to limit the horizontal excursions of the moored structures. In this case the dynamic position assistance is used to attenuate the slow drift oscillations, while the static mooring system opposes the steady forces. The most efficient DP systems incorporate numerical models to estimate the slow drift motions of the floating structure.

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doi:10.1016/j.oceaneng.2011.09.017

Over the recent years much research work has been focused on the hydrodynamics of floating structures in shallow water. This is due mainly to the development of offshore Liquefied Natural Gas (LNG) terminals. In shallow water the wave exciting drift forces increase in magnitude (Fonseca et al., 2008) and, on the other hand, these structures operate often in close proximity with other floating bodies like buoys, supply vessels, or offloading shuttle tankers. For these reasons an accurate prediction of wave exciting mean and slowly varying drift forces in shallow water is important. van der Valk and Watson (2005) presented a comprehensive set of model test results for different arrangements of an LNG carrier and floating production barge in moderate multi directional wave climates. The authors concluded that a good prediction and control of the motions during offloading operations from a floating platform to a LNG carrier is important.

The previous paragraphs demonstrate that wave exciting drift forces induce significant dynamic responses on floating structures, therefore it is important understand them and also to develop and validate numerical methods for their accurate prediction. The focus of the present study is on the slowly varying wave exciting drift forces. The related transfer function, also called quadratic transfer function (QTF), represents the amplitude of the second order harmonic force for all combinations of pairs of incident harmonic waves. Usually it is represented by a $N \times N$ matrix where N is the number of wave frequencies considered. The main diagonal corresponds to zero difference frequency, meaning mean drift forces in monochromatic waves. The usual procedure for calculation of slow drift forces is to simplify the QTF by representing the difference frequency components in terms of the zero difference results. In this way the second order problem is much simplified as well as the computational effort. However this approximation has some limitations. For the slow drift oscillations it may be important to consider correctly the difference frequency components, for example when the difference frequency is close to a motion resonant frequency and the amplified motions contribute significantly to the quadratic drift effects.

1.1. *Review of numerical methods*

The calculation of mean drift forces is usually carried out using one of two methods, the so-called far-field solution, or the near-field solution. Maruo (1960) applied the far-field method to represent the horizontal drift forces on two dimensional and three dimensional bodies considering incident harmonic waves and deep water. The solution is based on the assessment of the time rate of change of the momentum in the fluid within a control volume bounded by the free surface, the body, a vertical cylindrical surface with radius tending asymptotically to infinity and the ocean bottom. The force is obtained by averaging the former over one wave cycle. Newman (1967) applied the same method to derive the yaw drift moment in deep water, whereas Faltinsen and Michelsen (1974) modified Newman's (1967) formulation in conjunction with a three-dimensional sink—source technique and showed that his expressions were equally valid for infinite and finite water depth. The application of the far-field method for evaluating the mean second-order heave force and the roll and pitch moments leads to expressions that involve infinite integrals on the free surface supplemented by corresponding ones on the sea bottom, in case of finite depth waters. Lee and Newman (1971) circumvented this difficulty in the case of a submerged body in deep water by expressing the free-surface integrals in terms of Kochin functions evaluated on the mean position of the body's wetted surface. Mavrakos (1988) implemented the far-field formulation to present expressions for the mean vertical drift force and the pitching moment on free-surface piercing arbitrarily shaped vertical bodies of revolution floating in water of finite depth. The analytic representation of the velocity potential that can be established for this particular type of bodies in terms of Fourier series (see Kokkinowrachos et al., 1986), enables the evaluation of the infinite free-surface and sea-bottom integrals in closed form. For arbitrarily shaped bodies however, the momentum method cannot give the vertical drift forces, neither second order pressures on the body.

Pinkster and Van Oortmersen (1977) introduced the near field method to evaluate the mean drift loads on arbitrarily shaped large volume floating bodies in all six degrees of freedom. The method requires that all pressure contributions giving rise to second order terms with respect to the wave amplitude have to be correctly integrated over the instantaneous wetted surface of the body. The near field formulation is not restricted to the evaluation of mean forces only. It can be also applied for evaluating the second order sum- and difference-frequency wave load components. However, numerical schemes implementing panel formulations is much more sensitive to the meshing of the body's wetted surface, particularly near the free surface and close to sharp corners.

While the mean drift forces are calculated from quadratic products of first order quantities, the oscillatory component, or slow drift force, requires the calculation of second order potentials. This means that the hydrodynamic problem must be solved correctly up to the second order in the wave elevation. In that context, Pinkster (1976, 1980) implemented the near field solution to calculate the time dependent slowly-varying difference-frequency drift loads. In doing this, he accounted for all quadratic terms originated from the first-order potentials together with the second-order contributions arising from the undisturbed second-order incident wave field. Contributions due to second-order diffraction potential were omitted in his formulation. For their evaluation, two methods have been proposed in the literature classified as 'indirect' and 'direct'.

The first circumvent the direct calculation of the second-order diffracted wave field by introducing an assisting radiation potential (see for example Lighthill, 1979; Molin, 1979; Eatock Taylor and Hung,1987; Abul-Azm and Williams, 1988; Mavrakos and Peponis, 1992). These methods have been proven efficient in calculating the hydrodynamic loading. However, they cannot provide results for the second-order pressure wave field and the free surface elevation around the structure. The second class of solution methodologies, the so-called 'direct' methods, allows the derivation of the second-order diffraction potential. Examples of works in that context are those due to Loken (1986), Kim and Yue (1989, 1990), Scolan and Molin (1989), Chau and Eatock Taylor (1992), Zaraphonitis and Papanikolaou (1993), Huang and Eatock Taylor (1996), Eatock Taylor and Huang (1997), Malenica et al. (1999), Newman (2005), Mavrakos and Chatjigeorgiou (2006) and Chatjigeorgiou and Mavrakos, 2007.

More recently the so-called middle-field formulation was proposed to overcome the convergence problems of the near field method (Chen, 2005; Rezend et al., 2007). In this case the control surface is located at a finite distance from the body.

1.2. *Review of experimental work*

Experimental data from model tests is usually very useful to get insight into the psychics of the hydrodynamic problems. Additionally, experimental data is often needed to validate the numerical methods. In the case of the second order drift forces on marine structures, there are not many experimental results available in the literature. Kobayashi et al. (1985) present the horizontal mean wave drift force on a tension leg platform (TLP) in regular waves. Standing (1991) carried out model tests with a moored tanker in bi-chromatic waves and compares the measured slowly varying wave exciting surge force with numerical predictions. More recently some