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Estimating on-site wave spectra from the motions of a semi-submersible platform: An assessment based on model scale results

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ABSTRACT

This article presents the results of a preliminary investigation on the use of the motions of a large-volume semi-submersible platform as the basis for estimating waves on-site. The main focus of the application is on the harsher wave conditions, for which other measurement devices are known to present limitations. As a first step in this investigation, a series of tests were performed with a scaled model in a wave basin. A wide range of waves was tested in order to evaluate how the estimation errors behave with respect to wave period and amplitude. Moreover, since the statistical inference relies on a linear dynamic model, the influence of uncertainties on the unit's RAOs must be assessed. Since the non-linear viscous effect on resonant responses is known to be one of the main sources of error in this regard, different approaches for predefining the viscous damping levels are tested and compared. The results attest that, at least in the controlled conditions of the tests, the inference method is able to provide accurate estimations of the extreme waves conditions that were tested. A simple method for predicting the damping based on the recorded motions is shown to improve the estimations.

1. Introduction

Directional wave inference obtained from the records of vessels motions is a technique that has seen its application grow significantly over the last years. Usually, the main interest in this approach comes from the fact that this sort of estimation only requires simple instrumentation and hardware, which can be easily installed on-board and require little maintenance. Most of the previous works on the method based their estimations on ships or ship-shaped platforms, due to the fact that these vessels are known to have significant response even for mild wave conditions.

The major shortcoming of the method is that only waves that impose a reasonable level of motions to the vessel may be inferred. This is due to the fact that the vessel usually acts as a low-pass filter, filtering the high frequency components that do not excite the vessels first-order responses. Therefore, the larger the vessel, or the lower its response in waves, the more restricted will be the estimation range. The main motivation for this paper, however, arises from the fact that, although a semi-submersible is designed for responding only weakly to the incoming waves, it will still present significant motions in more severe wave conditions and, in these situations, it may perhaps provide a reliable account on the sea state that imposed such motions. For this reason, this method of wave inference is not intended for providing broad oceanographic records, but rather to be used as a means for identifying wave conditions that impose considerable motions on the vessel in which the system is based on.

Another practical reason that motivates the adoption of a large semi-submersible platform as a motion-based wave sensor is that the measuring systems that are widely considered as a global standard for wave data, such as wave buoys (Gemmrich et al., 2016) and wave radar systems (Fucile et al., 2016), may present some drawbacks in extreme weather conditions. For instance, wave buoys may be dragged through or swerve around the 3D peaks of waves (Allender et al., 1989). In addition, eventual presence of a spike in the raw accelerometer data (Mackay, 2009) may produce erratic maximum wave height measurements. Rough sea states and adverse weather conditions are also among the possible sources of errors in wave measurements from wave radar systems, since errors can be attributed to the shadowing effects produced by rain, large waves or sea spray, as well as the inherent bias of the system that could be increased by extreme sea conditions (Magnusson, 2008). Furthermore, all of them require important initial investments and/or high maintenance costs.

Consequences of these shortcomings are either way important for marine operations, engineering design and validation of forecasts of extreme wave events. In addition, comparisons between estimations

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obtained with wave buoys and wave radars have shown some important discrepancies (Durrant et al., 2009; Chen et al., 2013; Wijaya, 2009), highlighting the inherent biasses and differences in the performance of the sensors.

For the reasons exposed above, if proven feasible for real conditions, wave estimations obtained from the motions of a semi-submersible platform may provide an interesting complement to the readings of other devices in harsh seas. In fact, they are not expected to be affected by some of the factors mentioned above. On the other hand, it may have to deal with other problems, as for example the non-linear behavior of the motions (especially due to viscous damping effects) induced by the flow on the hull, risers and mooring lines. These aspects will be discussed with detail in this article.

From a general point of view, there are several approaches that may be considered for performing the wave inference based on the recorded motions of a vessel. As a first option, the wave spectrum can be estimated with a parametric modelling, with some examples of this method provided by: Hua and Palmquist (1994), where the wave conditions are estimated using the full-scale data, applying a variational method. Another work based in this research topic is presented by Tannuri et al. (2003), who used the data from a moored FPSO with a non-linear parametric model to estimate the directional wave spectrum. Montazeri and Nielsen (2014) use the parametric approach to estimate the directional wave spectrum from full-scale response measurements carried out on a container ship. One additional example of the parametric modelling approach can be found in Montazeri et al. (2015), which presents a trend analysis for prediction of sea state parameters using a JONSWAP model. Finally, Montazeri et al. (2016) is another recent work in which a parametric model of the directional wave spectrum is calibrated to estimate wind sea and swell based on motions of a ship.

Alternatively, another line of works proposes the estimation of the directional wave spectrum based on non-parametric modelling methods. The inference is then made using either the wave buoy analogy or the Bayesian modelling procedure. Regarding the wave buoy analogy, Nielsen and Stredulinsky (2012) obtain the estimations from full-scale motions measurements. The results are compared with real wave rider buoys and radar data. They show that the statistical parameters are accurately estimated when compared with the wave rider buoy, and the method provides a slightly better estimation when compared to the wave radar systems. Furthermore, Nielsen et al. (2016) aim to evaluate a novel concept for wave estimation using the wave buoy analogy using shipboard measurements, which in this case is formulated directly in the time domain combining different techniques and the least squares fitting to estimate wave amplitude and phase.

The so-called Bayesian modelling procedure has been adopted by Nielsen (2006), who presented derivations of both parametric and non-parametric theories. The theories for both methods are applied in order to obtain the directional wave spectrum from real scale data (radar) and numerical simulations. The same researcher (Nielsen, 2007) carried out a detailed study of numerical simulations of time histories, providing an estimation of the sea state parameters. In this work, two approaches are considered: the parametric procedure and the non-parametric one. The paper finally concludes that it is difficult to favor one particular method, since both of them provide similar results.

Simos et al. (2010) present a complete analysis of the sea states estimated from the motions of a model scale FPSO. These estimations are performed using the Bayesian inference method with two hyperparameters, as proposed by Nielsen (2008), but with a relevant conceptual change. Different from the original proposal, they have set a pre-calibration of these hyperparameters, meaning that the values of both were prescribed for each wave estimation. From a conceptual point of view, although the mathematical structure of the Bayesian model was preserved, an important feature of the Bayesian approach was abandoned, namely the adoption of an information criterion for searching the best values of the hyperparameters in each estimation event. This approach, however, led to a much more expedite estimation procedure, meanwhile the results obtained in the experimental campaign attested that the wave conditions could still be inferred with good accuracy.

Later, Simos et al. (2012) used full-scale data from an FPSO operating in Brazil's Campos basin for a first evaluation of the performance of this method in field conditions. However, due to the lack of alternative wave sensors, the comparison of the results was made almost exclusively with hindcast predictions provided by NOAA for the same region where the FPSO was operating. The authors concluded that the method was capable of inferring the sea states with a good agreement with the NOAA predictions, despite the inherent limitations concerning the estimation of sea states with low peak periods.

Bispo et al. (2016) presents the first part of the results from a new field campaign, started in December 2014. Again, results are obtained from full-scale FPSO motions using the Bayesian inference approach. The performance of the motion-based method is checked against the wave estimations provided by a commercial marine radar system. Comparisons between both systems attest an adequate identification of mean wave conditions.

The use of a semi-submersible platform to estimate extreme wave conditions was initially investigated by Wijaya (2009). As for the present paper, their work was also based in large part on model-scale tests. However, the analysis was based on a set of final design tests performed for the platform, which only comprised a short range of wave conditions.

In the present study, a scaled model of the same semi-submersible unit was built and tested in a large set of experimental conditions at the CH-TPN wave basin of the University of São Paulo. The experiments were specifically conceived for verifying the feasibility of performing the motion-based estimations, putting special emphasis on more severe wave conditions.

Next, a brief description of the statistical inference approach is presented (section 2), followed by the presentation of the semi-submersible unit adopted as a case study (section 3). Section 4 discusses the numerical modelling leading to the linear motion RAOs. It also addresses the importance of a proper damping estimation for predicting the heave resonant motions and the difficulties imposed by the non-linear character of the viscous effects. The experimental setup and the main features of the test campaign are presented in section 5. Section 6 brings the main results, confronting the directional wave spectra estimated by the model motions to those obtained from a set of conventional wave probes. Finally, section 7 draws the main conclusions and discusses further steps that should be taken in the continuity of the research.

2. Bayesian inference method

The non-parametric approach adopted in this study follows the Bayesian modelling procedure as proposed by Akaike (1980), which essentially aims at introducing different kinds of *a-priori* information to improve the ill-conditioned problem as well as to reduce the influence of noise. This central idea was used for the first time by Iseki and Ohtsu (2000) to estimate the wave spectrum from measured motions of a ship with forward speed. In their approach, the prior information essentially concerns the fact that the spreading of wave energy in direction should happen smoothly. The trade-off between the good fit to the data and the smoothness of the solution is then controlled through a single hyperparameter. Following these works, Nielsen (2008) proposed the introduction of an additional hyperparameter, which, in its turn, controls the smoothness of the energy distribution regarding the wave frequency. Common to all these previous applications of motion-based wave inference is the fact that the determination of the optimal value of the hyperparameters have been done by minimizing Akaike's Bayesian Information Criterion (ABIC), see e.g. Akaike (1980), despite the expensive computational cost that is required by this procedure.

Simos et al. (2012) and Bispo et al. (2016) used an approach similar to the one proposed by Nielsen (2008). In their case, however, applications were made for moored floating systems (therefore without advance speed) and a third hyperparameter was included, which avoids excessive