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Response predictions using the observed autocorrelation function

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A B S T R A C T

This article studies a procedure that facilitates short-*time*, deterministic predictions of the wave-induced motion of a marine vessel, where it is understood that the *future* motion of the vessel is calculated ahead of time. Such predictions are valuable to assist in the execution of many marine operations (crane lifts, helicopter landings, etc.), as a specific prediction can be used to inform whether it is safe, or not, to carry out the particular operation within the nearest time horizon. The examined prediction procedure relies on observations of the correlation structure of the wave-induced response in study. Thus, predicted (future) values ahead of time for a given time history recording are computed through a mathematical combination of the sample auto-correlation function and previous measurements recorded just prior to the moment of action. Importantly, the procedure does *not* need input about the exciting wave system, and neither does it rely on off-line training. In the article, the prediction procedure is applied to experimental data obtained through model-scale tests, and the procedure's predictive performance is investigated for various irregular wave scenarios. The presented results show that predictions can be successfully made in a time horizon corresponding to about 8–9 wave periods ahead of current time (the moment of action).

1. Introduction

Most marine operations require a high level of safety. This is also the case when concern is for here-and-now operations such as lifts by floating cranes, helicopter landings on (smaller) ships, tow of drilling and production vessels/platforms, and various ship-to-ship actions. The execution of these operations can be made safer if the particular vessels wave-induced motions can be predicted ahead of current time. Thus, the ability to calculate accurately, in a deterministic sense, the future wave-induced behaviour of the vessel can reduce significantly the probability of failure of the actual operation. Some of the before mentioned operations involve dynamically positioned (DP) vessels and one means to apply the predicted response/motion ahead of current time can, in this case, be used directly in proactive control strategies for the DP system. Examples of strategies may be to adjust the controller gains, change the set-point of smaller vessels, and for larger vessels accelerate the vessel into the waves to avoid drift-off, or, if worst comes to worst, have sufficient time to emergency-abort the operation safely. Other practices, where the prediction of vessel motions ahead of current time is valuable, occur for general heave compensation systems, and for robotic manipulators on ships and other seaborne platforms, since efficient operation of the manipulators requires precise motion planning and control algorithms. As a practical remark, it should be noted that *current time*, in the following, relates to the very instant from when a prediction is made, meaning that measurements have been recorded (are known) only until the current time. Equivalently, this specific time could be defined as the *moment of action* from when the future (hydrodynamic) behaviour of the vessel is predicted.

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1.1. Previous work

In the past, a number of studies has been conducted to investigate procedures for the prediction of the wave-induced motion of a marine vessel. Some of the initial studies, e.g., Dalzell [1], Triantafyllou et al. [2,3] and Sidar and Doolin [4], were concerned about the landing of aircrafts on naval destroyers. Since then, several of other works have followed both with naval and merchant applications; for instance, Broome [5], Broome and Hall [6], Chung et al. [7], Duan et al. [8], From et al. [9], Khan et al. [10–12], Naaijen et al. [13], Peng et al. [14], Woodacre et al. [15], Zhao et al. [16]. Most works in the existing literature belong to one of two main categories. Either the established prediction procedure relies on; a) a combined knowledge of the exciting wave system and the hydrodynamic behaviour of the ship, e.g. in terms of the ships transfer function, or b) the procedure relies on some sort of offline training which is necessary for 'standard' autoregressive (AR) models and Neural Networks that, on the other hand, not necessarily require input about the waves/sea state. Obviously, independence of (information about) the sea state is beneficial, as real-time ocean surface and sea state estimation, at a ship's exact location, in itself can be a difficult problem to handle in practice, not to mention the uncertainty associated to the actual estimate produced by whatever estimating means [17–19].

It is possible to formulate a prediction procedure, see Andersen et al. [20], which neither requires information about the wave conditions, nor does it require offline training. In the particular procedure - for any considered motion component - the sample autocorrelation function (ACF) for a *recent* time window needs to be obtained. The (sampled) ACF must represent a stationary situation which, in time and properties, is so close to the current time that the statistics and the correlation structure in the *dynamical system* have not changed significantly. Thus, leaving the basic details for later, the prediction procedure relies on a linear model based on the correlation structure, in terms of the autocorrelation function, of the physical process in question together with the most recent - past - measurement points. In this connection, it is important to realise that the autocorrelation function is a direct measure of the physical process' underlying memory effect; here due to the free surface oscillations of the sea surface. Another property to keep in mind, when discussing a process's memory and the autocorrelation function, is the fact that, for a stationary process, " … *the autocorrelation function and the spectrum are transforms of each other, (hence) they are mathematically equivalent*" [21]. This fact is made directly use of later, but, as a qualitative interpretation of the property, it means that an infinitely narrow-banded process has infinitely long prediction horizon; since the process has, in the extreme case, one single frequency component and, hence, is described by a sine wave. The opposite is true for an infinitely broad-banded process (i.e. white noise), where the deterministic prediction horizon is zero.

In a recent study, Nielsen and Jensen [22] investigated the procedure [20], to predict vessel responses up to 50 s ahead of current time. The study [22] was focused on simulated time histories of a ship's wave-induced vertical acceleration at the centreline at a longitudinal position forward of the COG. In total, 20×60 min of measurements data were simulated, and predictions, looking 50 s ahead, were made every 10 s within the single 60-min time strips. Hence, 7200 (= 3,600s/10s $\times$ 20) sets of {predictions vs. measurements} were analysed and statistically evaluated. The study showed that predictions of the acceleration level could be successfully made up to 20 s ahead of time for most of the sets (about 85–90%); however, with prediction accuracy reducing beyond this time to a success rate of 10–20% at the end of the prediction intervals (spanning 50 s). Various metrics were derived to establish the statistical comparison between the predictions and the (simulated) measurements but, obviously, there is no unique way of doing the comparison of individual time history strips; a fact which also will be addressed later in the present study.

1.2. Content of the study

The investigated procedure by Nielsen and Jensen [22] is also examined in the present study but, herein, the measurements data consist of motion recordings obtained from model-scale experiments rather than numerically simulated time histories. Some of the findings made in Ref. [22] are directly applied in the present work and, as such, the study herein is a continuation of the former one, including the recommended further work.

In most studies on stochastic wave-structure interactions, the statistical concept of a *stationary process* is important. Indeed, this is so herein and throughout it is a fundamental assumption that conditions are stationary. In principle, this calls for a discussion on requirements for a process to be stationary, or maybe rather a discussion of the theoretical/mathematical consequences if the process is not strictly (nor weakly) stationary. However, this particular discussion is not touched upon, although some remarks are given. Overall, the importance is that stationarity will be assumed; without necessarily stating this.

It should also be mentioned that the interest in this study concerns 'standard marine crafts', such as ships or other ship-like structures and floating platforms, and *not* tethered marine structures. On the other hand, the theoretical formulations might apply to the latter type of structures; *if* the particular response is characterised by a (Gaussian) stationary process.

1.3. Composition of paper

The paper has been organised into five main sections, and the remaining four are as follows: In Section 2, the theoretical formulations are outlined with mentioning also about general properties about the (sample) autocorrelation function of a stationary process. The experimental facility, including descriptions of the test cases, and pre-analyses of the recorded model-scale data are described in Section 3. All predictions, and associated results and comparisons with measurements, follow in Section 4. Finally, a short summary and an extraction of main findings and conclusions are given in Section 5.