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Ocean wave characteristics prediction and its load estimation on marine structures: A transfer learning approach

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ABSTRACT

Statistical and stochastic approaches, commonly used to estimate wave induced loads in the marine and coastal structural analysis and design of offshore vessels and platform, require accurate sea state or wave characteristics, which are usually estimated using computationally intensive numerical wave models. While advances in machine learning helps to overcome the computational challenges of these approaches, they still need measurement of historic data at the region of interest to help prospective estimation of wave loads. This calls for deployment of sensors and allied resources for continuous monitoring and collection of streaming data. Transfer learning, on the other hand, provides a framework to derive representations from an existing region to estimate the characteristics in the region of interest. Deep Belief Networks are excellent candidates for latent representation of the relationship between the different sea state characteristics and the induced loads. In this paper, we first train a DBN based wave characteristic prediction model to predict the sea state characteristics (namely, significant wave height H_s, dominant or peak wave period T_p and average or zero crossing period T_z) using data from 12 stations at 3 geologically different regions (the Gulf of Mexico, the Korean Region and the UK region), using data between the period Jan 1, 2011 and Dec 31, 2014. We validate the model using data in these regions between Jan 1, 2015 and Aug 30, 2015. We then compute the effect of the wave characteristics, namely, the wave-drift force and moment on 12 different marine structures with both regular and irregular waves. Finally, we transfer the DBN representations to predict the sea state characteristics in Irish region for the same period. Evaluations against ground truth and comparisons with state-of-the-art methods show the superior transfer learning performance of the DBN and accurate computations of the wave drift force and moments.

1. Introduction

The design, construction and operations of marine, coastal and harbour structures are predominantly influenced by environmental loads such as wind, waves, current, tides, earthquake, temperature, ice, seabed movement and marine growth. Of these environmental loads, the wave-induced loads are very critical for several offshore activities such as drilling, oil and gas platforms, transportation, fisheries, navy, port traffic management, dredging, harbour activities, coastal disaster management [1-5], and it has major effects on marine, offshore, coastal and harbour structures [6]. Moreover, an accurate and rapid prediction of wave-induced loads are essential for emergency evacuation of manned platforms and disasters like oil spills. In addition, prediction of wave height, its period and wave spectra are also very important for the analysis of climatic conditions since it helps in exchange of heat and

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energy across atmosphere and ocean. Therefore prediction of these wave characteristics plays a crucial role in the assessment of loads due to both the regular and irregular waves, on marine, coastal and harbour structures and model testing.

Although the effect of both regular and irregular waves on marine, coastal and harbour structures must be considered for structural design and strength analysis [7,8], earlier studies considered only the effect of regular waves. For instance, the response of marine structures to regular waves can be determined by many statistical methods such as Airy wave theory [9], solitary wave theory [10], stream function wave theory [11] and conoidal wave theory [6]. On the other hand, the random irregular waves that represent the real sea state are modelled through wave energy spectrum such as the Pierson-Moskowitz (PM) spectrum and JONSWAP spectrum. The PM-spectrum was originally proposed for fully developed sea [12] and the JONSWAP spectrum extends PM to include fetch limited seas [13]. Although, these spectra describe wind sea conditions of severe sea states, they do not address the needs of moderate and low sea states in open sea areas that are often composed of both wind sea and swell. The Ochi-Hubble spectrum [14] and Torsethaugen spectrum [15] represents severe, moderate and low sea states. They are predominantly used to model the two peak wave energy spectra but in practice the resulting total spectrum typically has only one peak. Torsethaugen spectrum in particular is suited for North Sea conditions. These spectra are often defined in terms of significant wave height (H_s), peak wave period (T_p) and/or zero-crossing period (T_z). Thus, it is evident that (a) there are several models that are specific to each sea states and wave types, and clear judgement of the sea state and wave types are critical in choosing an appropriate model and (b) all these models involve computationally intensive and cumbersome statistical, mathematical approaches.

In addition to numerical methods, the wave characteristics are also predicted using radar images and satellite altimeters. The estimation of H_s and T_z are attempted through direct detection of shadowed area in X-band radar images [16], but the estimation shows large deviations from measured values due to the application of two different measurement principles. In Ref. [17], H_s and T_p are estimated using an empirical orthogonal function (EOF), however, the results are not good as not all EOF modes are considered. A passive remote sensing method based on reflectometry is used to measure H_s in Ref. [18]. This method is affected by the height of the installed receiver. Thus, the methods using X-band radar images and satellite altimeters require high quality images and highly efficient image processing algorithms for better estimation of wave heights and other characteristics.

With the recent advances in the development of soft computing methods, there is an increasing interest in leveraging on these methods to predict wave characteristics, and to study their effects on marine vessels [19]. Of the soft computing methods, neural networks have the proven ability to approximate any complex non-linear process without *a priori* knowledge of the underlying physics. Current numerical and soft-computing methods are used to predict the wave characteristics in regions where historic data is available and collected. However, the effect of the predicted wave characteristics on marine structures is not evident and unavailability of historical data in new regions of interest impedes the understanding of wave characteristics during exploration of the region. Therefore, it is important to leverage on the established relationship between the environment and wave characteristics from existing regions, to compute the wave loads on marine, coastal and harbour structures and predict the wave characteristics at a new region of interest. In this work, the wave loads on marine structures are computed for both regular and irregular waves based on the predicted wave characteristics. To validate the computation of wave loads, we first compute wave loads on a FPSO vessel and compare it with the experimental measurements as in Ref. [20]. Transfer learning provides a framework to achieve this objective. DBN provides a good platform for transfer learning, as it helps to learn and represent latent representations that can be generalized across the problem domain [21,22]. Recently, DBN was used to transfer learn representations about wind characteristics to enable identifying new sites for wind mill installations [22]. In this paper, we use DBN to transfer learn the representations of wave characteristics to enable predictions in new regions of interest. The DBN representations are learnt from data acquired from 12 stations at 3 geologically different regions: Gulf of mexico (GoM), Korean region (KR) and UK region (UKR). The learnt representations are then used to predict the wave characteristics at 5 stations from Irish region, and compared against the ground truth. Performance studies, in comparison with other state-of-the-art methods, show the superior prediction and transfer learning abilities of DBN. It can thus be established that the trained DBN model can be used to predict wave characteristics and identify new regions for offshore activity. The main contributions of this paper are as listed below:

- Wave Characteristics Prediction Model Development: We use a deep boltzmann architecture to represent the latent representations that describe the wave characteristics. For the first time in literature, we develop a deep architecture to predict multiple wave characteristics such as significant wave height, peak wave period and the zero-crossing period.
- Computation of Wave Loads: Based on the predicted wave characteristics, we compute the wave loads on marine structures due to regular and irregular waves. For the first time in literature, we consider the effect of drag coefficient of current flow (C_D). This is important as C_D is an important influencer of sea state conditions.
- Wave Characteristics Prediction in new region of interest: We demonstrate that the latent representations of DBN can be used to predict wave characteristics in a new region of interest. Thus, the developed model can be used to predict wave characteristics, and hence their effect on marine structures, in region where historical data is not available.

This paper is organized as follows: We briefly describe the formulation of wave loads in Section 2. Section 3.1 presents the details of the data set and the overview of the proposed approach. In section 4, we present the results of (a) Validation for prediction of wave characteristics in Gulf of Mexico, Korean region and UK region (b) Effects of the regular and irregular waves on the marine structures and (c) Prediction of wave characteristics in Irish region, through transfer learning. Finally, section 5 summarizes the conclusions.