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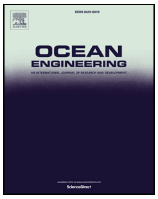

Methodology for assessment of operational limits including uncertainties in wave spectral energy distribution for safe execution of marine operations

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ABSTRACT

Marine operations need to be executed in a cost-effective and safe manner. Safety depends on safety margins that are included in the operational limits. These operational limits are normally given in terms of sea state parameters, i.e. significant wave height (Hs) and peak period (Tp), here denoted as Hs(Tp). Safety margins on Hs(Tp) should account for various sources of uncertainties in weather forecasts, wave spectral shape, numerical models, etc. Wave spectra at an offshore site may be multi-modal and not necessarily resemble analytical spectra, such as Joint North Sea Wave Project (JONSWAP) or Pierson-Moskowitz (PM) models. Since floating vessels are sensitive to wave spectral energy distribution, Hs(Tp) operational limits should account for this source of uncertainty. This paper provides a general methodology to assess the uncertainty in Hs(Tp) limits due to variability in wave spectral energy distribution. This is important for safe execution of marine operations. The methodology uses response-based operational limits, directional (2D) hindcast wave spectra and dynamic coupled models of marine operation activities. A case study of an offshore wind turbine transition piece installation is shown to illustrate the proposed methodology.

1. Introduction

Marine operations, such as towing, heavy lifting and float-over, are normally executed following operational procedures, in which the duration and operational limits for each activity are provided. These operational limits are given in terms of environmental parameters such as significant wave height (Hs), peak period (Tp) and wind speed (Vw), and in terms of dynamic vessel responses. This is because these parameters are practical and can be measured on-board. However, these operational limits are often set based on experience of marine installation contractors, and thus, they are not derived systematically using a validated numerical model (Peace et al., 1985; Clauss and Riekert, 1990).

For operations dominated by waves, operational limits expressed in terms of Hs and Tp, which are commonly denoted as Hs(Tp) should be derived systematically and provide the same safety level as the allowable limit of a dynamic response or a structural capacity. For example, a crane or lifting wire capacity is the operational limit of a heavy lifting operation. For pipelaying operations, Clauss et al. (1998) developed a numerical method to transform the allowable stresses in the pipe into Hs(Tp) limits. Moreover, Guachamin Acero et al. (2016b) proposed a general methodology to express allowable structural or motion responses in terms of allowable limits of sea states Hs(Tp). These limits are response-based and practical, and they provide the same safety levels as the structural capacity of structural components. This general methodology has already been applied in analyses of various marine operations (Li et al., 2016a; b; Guachamin Acero et al., 2017b).

To date, state-of-the-art offshore standards for planning and execution of marine operations such as DNV (2011a), DNV GL (2015) and ISO (2015), recommend that the operational limits should be expressed in terms of Hs. However, Tp is not taken into consideration, which is a relevant parameter for floating vessels.

Operational limits described above are deterministic, and thus, these limits do not account for various sources of uncertainties in forecasted wave parameters, numerical models, human decisions, etc. An assessment of these sources of uncertainties is necessary for safe execution of marine operations.

The Hs operational limits recommended by DNV (2011a), DNV GL (2015) and ISO (2015) are reduced by alpha factors that account for uncertainties in weather forecast. These alpha factors depend on the duration of operations, the threshold levels of these limits and whether or not meteorologists or measurement equipment are available on site. Alternatively, instead of alpha factors, uncertainties in forecasted Hs and Tp parameters can be assessed statistically from the error

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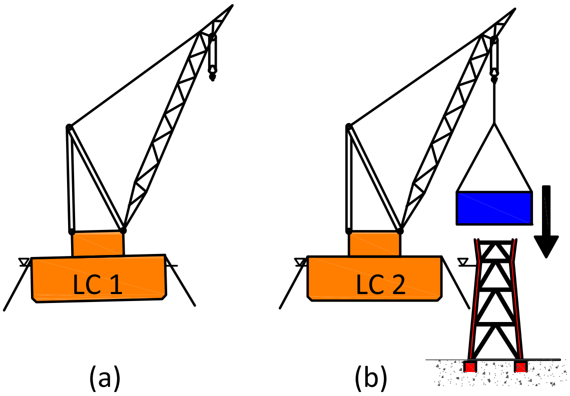

Fig. 1. Loading conditions. (a) Monitoring phase prior to installation LC 1; (b) Non-stationary lowering operation LC 2; (c) Stationary hanging condition LC 3.

distributions between the forecasted and the hindcast or measured wave parameters (Natskår et al., 2015; De Girolamo et al., 2017). Operational limits together with weather forecasts can be used to find workable weather windows for safe execution of marine operations.

To reduce uncertainties in weather forecast, Gintautas and Sørensen (2017) proposed a methodology that combines ensembles of weather forecast with on-board time-domain simulations. Workable weather windows are obtained by directly comparing the structural capacity (or allowable responses of structures) with the predicted dynamic responses using weather forecasts. Although this approach reduces uncertainties in forecasted Hs and Tp, the wave spectra used for the dynamic analyses are the analytical Joint North Sea Wave Project (JONSWAP) or the Pierson-Moskowitz (PM) wave spectral models. The wave spectra at sea may be multi-modal and not necessarily resemble the analytical spectra, and thus, both spectra may predict different responses.

To reduce uncertainties in dynamic responses of vessels, investigations were carried out by the European Commission (EU) project: Safe Offloading from Floating LNG Platforms (Safe Offload). In this project, dynamic responses were assessed by considering wind sea and swell components separately. This is done to develop strategies for heading selection when planning the operations (Hagen et al., 2015; Ewans and Jameson, 2015; Bitner-Gregersen, 2015). Moreover, an interactive simulator was developed for training of personnel and for testing critical operations (Varela and Guedes Soares, 2015). Simulators are necessary to set operational limits on motion responses or environmental parameters and to reduce the risk of failure during execution of marine operations.

From the information given above, it is observed that both environmental parameters and allowable dynamic responses of structures can be used as operational limits. These limits can be modified to account for uncertainties in forecasted wave parameters. However, even if the forecasted Hs(Tp) wave parameters are accurate, there will be differences between the measured and calculated dynamic responses of offshore structures. This is because the wave energy distribution or the spectral shape of the analytical and the hindcast or forecasted wave spectra are different. In fact, measured wave spectra can be multi-modal with several peak periods and directional components.

Operational limits in terms of Hs(Tp) are normally established during the planning phase. They depend on the dynamic responses of the floating structures under action of short-crested seas, which are generally modeled using analytical JONSWAP or PM formulations. Thus, Hs(Tp) limits depend on these input wave spectra. Since analytical wave spectra may not resemble the actual forecasted or measured directional (2D) spectra in open seas, unexpected responses of floating vessels during execution of a marine operation can occur. This also implies that the safety level in structural components can be lower than expected. Hs(Tp) limits should be simple and practical to be used onboar vessels, but they need to account for uncertainties in wave spectral energy distribution.

This paper aims at providing a general methodology to express operational limits in terms of Hs(Tp) that include uncertainties in wave spectral energy distribution. This is necessary for planning and safe execution of marine operations. Other environmental parameters such as current and wind speed are not considered. This paper firstly provides an introduction to the state-of-the-art techniques for assessment of operational limits. Then, a methodology for systematic derivation of Hs(Tp) limits is discussed. This methodology is the basis for the development of the new general methodology that includes uncertainties in wave spectral energy distribution. The new methodology is applied to a case study of an offshore wind turbine transition piece installation.

2. Response-based operational limits and directional wave spectra

This section provides a brief introduction to a state-of-the-art method for systematic derivation of response-based operational limits, and the basis for assessment of uncertainties in operational limits using analytical formulations of directional wave spectra such as JONSWAP or PM. This is necessary for development of a new methodology introduced in the Sec. 3.

2.1. Response-based operational limits

Guachamin Acero et al. (2016b) proposed a methodology for systematic assessment of response-based operational limits of marine operations. Based on this methodology, a response parameter such as motion or structural capacity can be expressed in terms of allowable limits of sea states Hs(Tp). The authors recommended a procedure to assess the dynamic responses of an operation, and to identify a response that limit an operation. Take as an example the installation of a topside module onto a jacket structure. Fig. 1 shows three loading conditions for the operation.

- Loading condition LC 1 corresponds to a monitoring phase, where the structure responses are monitored prior to lifting the module.
- Loading condition LC 2 refers to the actual non-stationary lowering of the module onto the jacket and the winch of the crane is running with a certain speed in this condition.
- Loading condition LC 3 is a stationary condition and is similar to LC 2, but does not include a running winch. For these loading conditions, Fig. 2 shows the allowable limits of environmental and dynamic response parameters that can be used for safe execution of such operation.

For the load condition LC 2 shown in Fig. 1 (b), the parameter that limits the operation (limiting parameter) is the impact force between the module and the jacket structure, see Fig. 2 (b). By conducting repetitive simulations of the module lowering operation, a characteristic