ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering

On long-term fatigue damage estimation for a floating offshore wind turbine using a surrogate model

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SUMMARY:
Of interest in this study is the evaluation of fatigue damage for a 5-MW offshore wind turbine supported by a semi-submersible floating platform. In particular, the base fore-aft bending moment and fairlead tension on a mooring line are investigated. This integrated turbine-platform-moooring system is sited in 200 meters of water. Metocean data provide information on joint statistics of wind speed, wave height and wave period along with their relative likelihood for a specific installation site in the Mediterranean Sea, near the coast of Sicily. A frequency-domain model is employed to provide needed power spectra for the desired response processes. With the ultimate goal of efficient evaluation of fatigue limit states for such floating offshore wind turbine systems, a computational framework is proposed to identify a surrogate model through a Gaussian process regression that relies only on assessing a small subset of representative sea states. This study makes it possible to quantify the relative influence of different sea states toward fatigue damage. The surrogate model itself offers an efficient alternative evaluation of all sea states and avoids excessive response simulations, while remaining accurate.

Keywords: fatigue, Gaussian process, offshore wind energy, floating offshore wind turbines

1. INTRODUCTION

The evaluation of fatigue and ultimate limit in different components of FOWT systems is important (Hsu et al., 2017; Thies et al., 2014). Various sea states at an offshore site in the Mediterranean Sea are selected for selected short-term fatigue damage evaluations for an FOWT supported by a semi-submersible platform. These sea states must be evaluaeed to address the long-term reliability against fatigue limit states (Marino et al., 2017; Ziegler et al., 2015). Aero-hydro-servo-elastic time-domain simulations can be computationally very expensive. As an alternative, we present an efficient fatigue damage assessment framework based on a coupled frequency-domain model. Our proposed approach combines the carefully selected sea states with a Gaussian Process (GP) surrogate model (Roberts et al., 2013) constructed from this subset of metocean conditions.

2. METHODOLOGY

Fatigue damage assessment is demonstrated for the OC4 DeepCwind 5-MW FOWT, designed for a water depth of 200 m (Robertson and Jonkman, 2014. The support structure is a semi-submersible floater anchored to the seabed by three catenary mooring lines (see Fig. 1 (left)).

2.1. Coupled Simulations in the Frequency Domain

Response simulations for the selected grid of sea states are performed by employing a coupled frequency-domain (FD) formulation. The FOWT is modeled as a 7-DoF system, with 6 DoFs related to the floater's rigid-body motions and one accounting for the wind turbine tower-top deflection in the fore-aft direction. From the system response in the selected sea states, PSDs of the normal stresses in the mooring lines and at the tower base are evaluated (Ferri and Marino, 2023; Ferri, Marino, et al., 2022) (see Fig. 1 (left)).

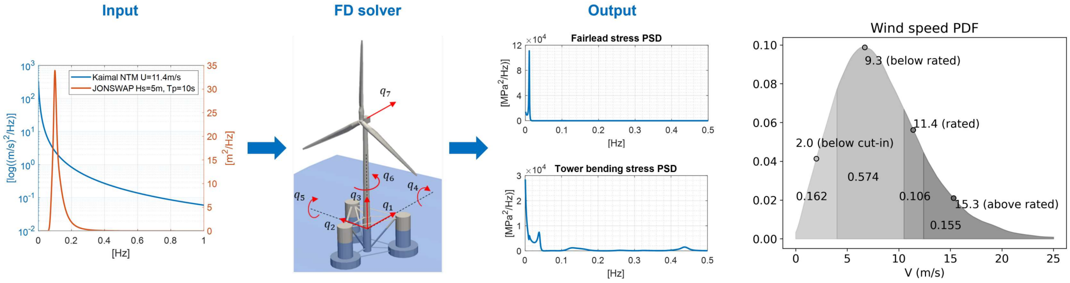

Figure 1. (left) Coupled FD model and stress PSDs. (right) Definition of wind speed bins.

2.2. Metocean Data Analysis

Hourly metocean data on hub-height wind speed (V), significant wave height (H_s) and wave peak period (T_p) from January 1993 to June 2021 are available for the selected site (Fig. 1 (right) and Fig. 2), where kernel density fits can be helpful for non-parametric metocean models (used also in extreme loads evaluations) (Manuel et al., 2018).

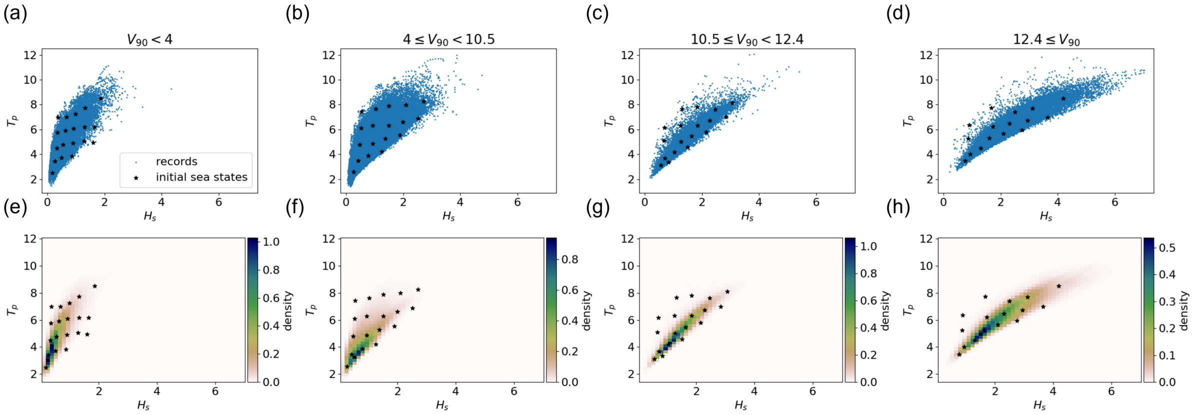

Figure 2. (a-d) Wave height and period data; and (e-h) kernel density fits for sea states in the 4 wind speed bins.

2.3. Fatigue Damage Assessment

Dirlik's method (Dirlik, 1985; Dirlik and Benasciutti, 2021; Ragan and Manuel, 2007), proposed here, allows simplified estimation of accumulated fatigue damage, $D(T)$, in time, T and of a "1-Hz damage-equivalent load", $DEL_{\text{1-Hz}}(T)$ in terms of moments of stress PSDs.

2.4. Gaussian Process Regression

A GP surrogate model (Roberts et al., 2013) makes use of $DEL_{\text{1-Hz}}$ estimates at selected sea states and provides an efficient long-term fatigue damage assessment that uses short-term GP surrogate surfaces and metocean wave statistics sampling as shown in Fig. 3.

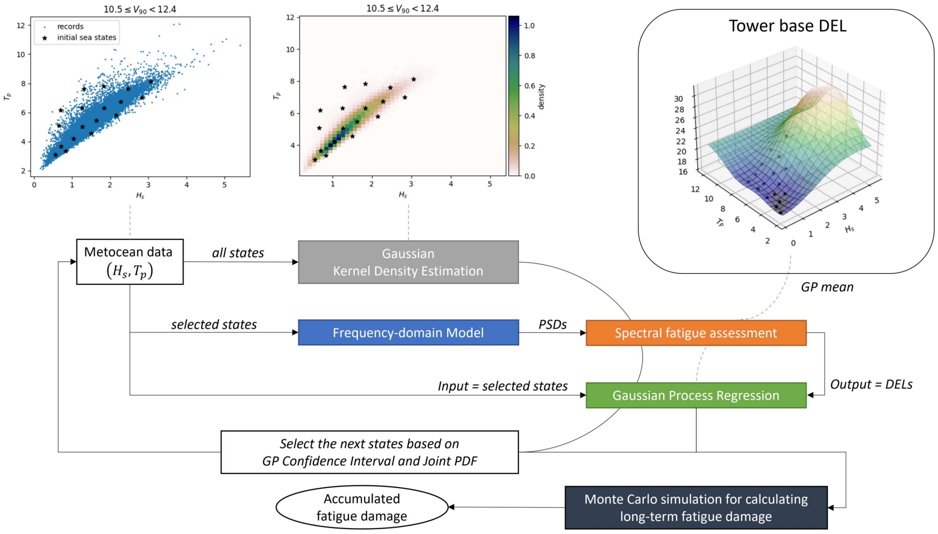

Figure 3. Framework for long-term fatigue damage assessment based on a surrogate GP regression model.

3. RESULTS AND DISCUSSION

Simulations in the frequency domain are performed by applying input wind and wave power spectra shown in Fig. 1 (left). Power spectra of tower and mooring line stresses are computed (Ferri and Marino, 2023; Ferri, Marino, et al., 2022). For fatigue damage assessment, needed material parameters are employed (Veritas, 2005). Representative response surfaces showing the 1-Hz damage-equivalent load, *DEL*, over 1 hour (3,600 cycles) are shown in Fig. 4. Additional sea states (see Fig. 5) are selected for GP improvement that reduce uncertainty and account for sea state probability. Finally, in Fig. 6, Monte Carlo (MC) sampling of sea states is used with the GP model, where different numbers of MC samples (10^0 to 10^5) are repeated 100 times so as to represent variability through box plots and show convergence rates. The 1-hour fatigue damage $D(T = 3600\text{s})$ is 3.0×10^{-5} for the tower base and 4.1×10^{-5} for the mooring line. Results indicate that the mooring line is more critical than tower base when one considers fatigue limit states.

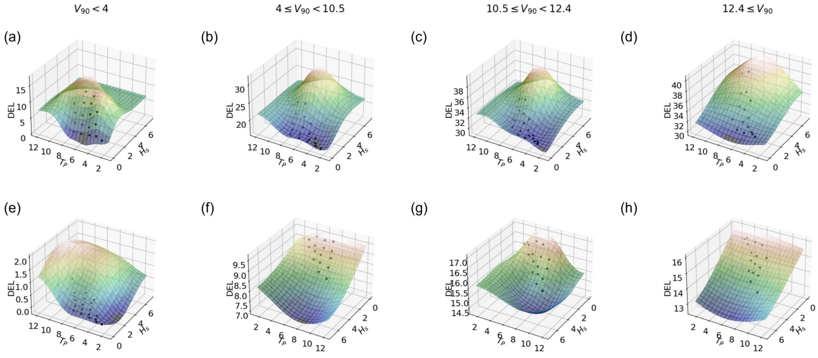

Figure 4. Response surfaces for the 1-Hz *DEL* (MPa) for stresses in (a-d) the tower base and (e-h) the mooring line.

4. CONCLUSIONS

Using representative sea states, we estimated fatigue damage for an FOWT. GP regression helped generate two-dimensional response surfaces of fatigue damage for each sea state. Long-term fa-

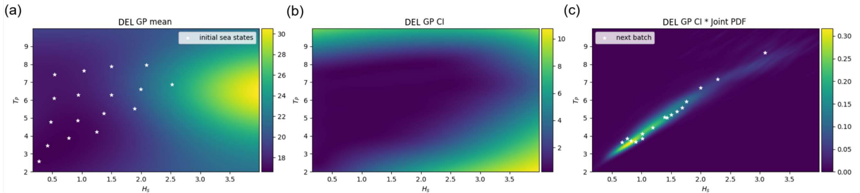

Figure 5. (a) 2-D response surface; (b) confidence interval (CIs); and (c) product of GP CI and sea state joint PDF.

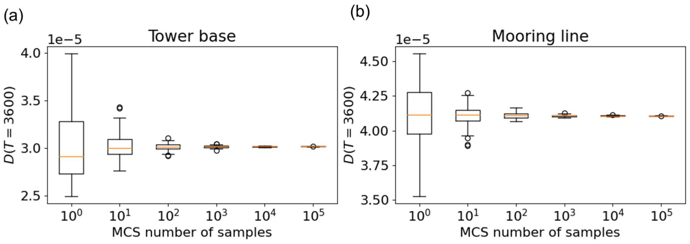

Figure 6. Box plots of accumulated 1-hr fatigue damage for (a) the tower base and (b) the mooring line.

tigue damage was then estimated through Monte Carlo simulations. Results indicate that the mooring line may be more critical than the tower base when evaluating fatigue limit states.

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