

Surrogate Modelling Approach for Reliability-Based Design Optimization of a Semi-Taut Mooring System of a Floating Offshore Wind Turbine

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1 Introduction

Reducing the cost of floating offshore wind turbines (FOWTs) while ensuring their safety remains a significant challenge. One promising approach is to optimize critical components, such as mooring systems, by balancing material efficiency with structural reliability. Reliability-Based Design Optimization (RBDO) offers a robust alternative to traditional deterministic methods as it incorporates uncertainties in material properties, manufacturing tolerances, and environmental conditions. By minimizing the probability of failure, RBDO enables cost-effective and reliable designs - a key consideration for offshore wind farms operating in remote and harsh environments. This study focuses on the optimization of mooring systems, which are crucial for maintaining the structural integrity of FOWTs. Given the high costs associated with mooring failures, it is essential to account for uncertainties in load calculations, particularly for ultimate and fatigue limit states, which are driving the mooring design [1]. In early design stages, frequency-domain approaches are especially attractive for computing limit states due to their computational efficiency and ability to approximate key system behaviors. In [2], the frequency-domain model effectively captures the main trends in FWT motion and tension statistics but tends to provide conservative fatigue damage estimates. Indeed, because frequency models do not account for some nonlinear hydrodynamic loads on the structure, they often yield to conservative fatigue estimates [2][3], and can also lead to significant under-prediction of mooring line tensions [4]. To achieve more accurate estimations of ultimate and fatigue loads, this study prioritizes time-domain simulations. However, these high-fidelity simulations are computationally expensive, limiting the size of the design space that can be explored. To address this challenge, the development of surrogate models is proposed to accelerate the computation of the limit states in the optimization process. This work outlines the implementation of two surrogate models: one for predicting extreme loads and another for fatigue loads. The process involves selecting a Design of Experiments (DoE) of feasible designs through an automated design evaluation framework, similar to the approach developed by Yildirim et al. [5], but adapted for the semi-taut mooring use case. Insights from this approach will guide the identification of key design driving constraints, sensitivity analysis, and potential dimensionality reduction. These findings will support the implementation of constraints in the optimization problem later in the project and enhance the efficiency of the RBDO process for mooring systems in FOWTs.

2 Definition of the problems and challenges

2.1 Context, System definition and specifications

The work is part of the European project TAILWIND. TAILWIND is focused on station-keeping systems of FOWTs, which comprise mooring lines and anchoring systems. The project will unlock identified opportunities for cost reduction, reduced environmental impact and material use, and also supply chain diversification.

The system used in this study is a semi-sub floater coupled with the IEA 15MW turbine, with a semi-taut mooring system of chain-polyester-chain lines designed for the Utsira North site. This configuration takes advantage of the strength and durability of chains near the anchors while utilizing lightweight polyester ropes to reduce tension

and environmental footprint. The hybrid design aims to balance cost-effectiveness, reliability, and minimal seabed impact, making it a practical solution for deepwater floating wind applications.

2.2 RBDO problem definition

The optimization problem can be formulated as follows:

Find: $X = \{x_1, x_2, \dots, x_k\}$

Minimize: $f_i(X)$, $i = 1, \dots, l$

Subject to: $h_i(X) = 0$, $i = 1, \dots, m$ and $g_i(X) \leq 0$, $i = 1, \dots, n$

Here, x_i represents the design variables, f_i the objective functions, and h_i and g_i the equality and inequality constraints, respectively. For this study, the objective functions include minimizing the Levelized Cost of Energy (LCOE) of a single unit and achieving a target reliability in fatigue and ultimate limit states for both the chain and polyester sections (i.e. $f_2(X) = \beta_{\text{FLS, top chain}} - \beta_{\text{target, top chain}}$).

Design variables under consideration, are selected from the literature [2][6]: chain diameter, polyester rope diameter, polyester rope length, top chain length and horizontal distance from the anchor to the fairlead.

Constraints are defined to ensure feasible designs, regarding system integrity and performance. Key considerations include limiting floater excursions to protect cable integrity, constraining horizontal and vertical accelerations at the RNA, and restricting yaw angles during operation. Additionally, tilt angle limitations ensure stability and performance across load cases. Further, seabed contact is restricted for long-term safety, and measures are taken to prevent slacking—which accelerates fatigue and ultimate limit states—and to avoid anchor uplift forces.

2.3 Challenges

As stated in the introduction, two key challenges arise from this optimization problem:

1. **High Cost of Limit State Evaluation:** Evaluating limit states, such as extreme loads and fatigue life, requires a large number of time-domain simulations. These simulations, while accurate, are computationally expensive. To address this, surrogate models can be employed to approximate the system's behavior, reducing the number of required simulations without compromising accuracy.
2. **Numerous Constraints and Their Evaluation Costs:** The optimization loop involves a large number of constraints that must be evaluated at each iteration. Some of these constraints are computationally intensive, which increases the overall cost. To manage this, two strategies are proposed, and their potential implementation will be analyzed based on the findings of this work:
 - *Pre-Optimization Design Space Reduction:* The design space can be reduced by filtering out infeasible designs based on simpler constraints before moving into the optimization process [1].
 - *Hierarchical Constraint Evaluation:* A weighted system for constraint evaluation could be implemented during optimization. Simpler constraints would be evaluated first, and only if these are satisfied would more complex and costly constraints be assessed. This tiered approach helps minimize unnecessary iterations on infeasible designs [6].

By combining surrogate modeling, design space reduction, and hierarchical constraint evaluation, the optimization process can become more efficient and scalable. This will enable effective exploration of the design space while managing computational demands.

3 Methodology

This presentation will detail the methodology used to develop surrogate models for the RBDO loop. The process begins with sampling design points from a design evaluation framework, as illustrated in Figure 1. The final Design of Experiments (DoE) will incorporate sampled points based on the site-specific metocean distribution. Particular attention will be given to the sampling of environmental variables to ensure the development of two surrogate models: one optimized for accurately predicting DELs from the bulk of the distribution and another tailored for capturing the tails of the distribution. Proper sampling is critical for ensuring the accuracy and reliability of the surrogate models. The database for these surrogate models is generated from time-domain simulations of the complete system using OpenFAST [7]. DELs are calculated using RainFlow counting and Palmgren-Miner's rule,

which are applied to the simulated mooring line tension time series. Finally, the presentation will analyze the findings from the design evaluation framework. This includes identifying design-driving constraints, performing sensitivity analysis, and reducing the design space to improve optimization efficiency.

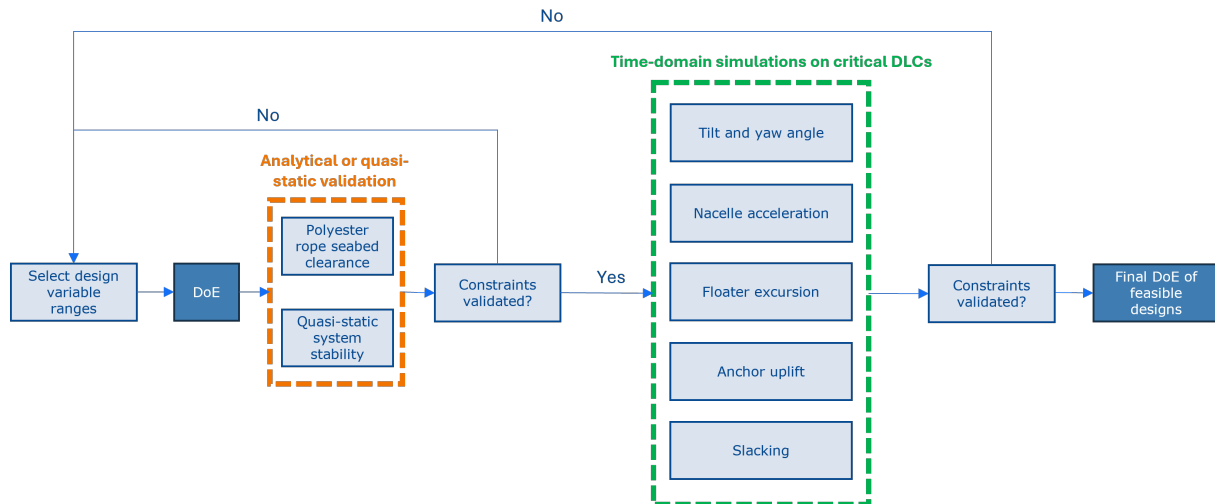


Figure 1: Design Evaluation Framework for input design variables DoE definition.

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