Optimization with Reliability Constraints. Application: Mooring System of Offshore Floating Wind Turbine

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Abstract:

Offshore wind turbines are a very promising field in renewable energy. They are able to reduce many limitations of onshore wind turbines. Current fixed offshore platforms are however economically limited to water depth less than about 60 m. To alleviate this limit, floating wind turbines, involving floating platform with mooring system, are proposed. This technology is currently in development and its cost is carefully studied. In such phases of development, it faces a lot of challenges, technical and economical. The application case we consider is the design of the moorings lines. Our work is concerned with the problem of structural design optimization in the presence of uncertainty. The optimization consists in minimizing the design cost for moorings lines while ensuring the reliability of the system which is measured by a probability of failure.

Reliability of the system is characterized by verifying three requirements : resistance against the fatigue [8], avoiding unsafe configurations and ensuring good connections between the moorings lines and the floater. In material science, fatigue is the weakening of a material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The fatigue life estimation can be calculated under the assumption of linear cumulative damage. Let us denote : $\boldsymbol{x}$ the design vector characterizing the mooring system, $\boldsymbol{\xi}$ the random vector modeling the uncertainty in the evaluation of the accumulated damage over the lifespan $[0,T]$ and $\boldsymbol{X}_{LT}(t)$ the vector-valued stationary and ergodic random process which describes the random characteristics of the marine environment (with a discrete stationary probability distribution $\mathbb{P}_{\boldsymbol{X}_{LT}}$ given by a scatter diagram). Considering the ergodic theorem and the accumulative nature of the damage, we calculate the total damage g over the time interval $[0,T]$, and at a given position along a mooring line s, as following :

$$g(\boldsymbol{x},s,\boldsymbol{\xi}) = \int_0^T G\left(\boldsymbol{x},s,\boldsymbol{\xi},\boldsymbol{X}_{LT}(t)\right) dt \simeq T\,\mathbb{E}_{\boldsymbol{X}_{LT}}\left[G\left(\boldsymbol{x},s,\boldsymbol{\xi},\boldsymbol{X}_{LT}\right)\right], \tag{1}$$

where $G(\boldsymbol{x},s,\boldsymbol{\xi},\boldsymbol{X}_{LT})$ represents the damage rate for the sea state environment $\boldsymbol{X}_{LT}$. A damage rate value can be evaluated by DeepLines$^{\text{TM}}$, which is a Finite Element software dedicated to modeling offshore floating structures in their marine environment. DeepLines$^{\text{TM}}$ is adapted for time as well as spectral domain computation of the equation of motion. The frequency domain analysis provides results that are consistent with the time-domain simulations for the moderate and most frequent X_{LT} sea states [5]. The input is a power spectral density of a stationary Gaussian process that characterizes the sea state. The power spectral density belongs to the family of JONSWAP spectra [3], used to modelize the waves, which are parameterized by $\boldsymbol{X}_{LT}$.

After appropriate linearization of the nonlinear term that appears in the Morison equation [7, 4], the output of the system is the Response Amplitude Operator (RAO) which represents the transfer function of the tension range for each line, while subjected to the wave and wind loading. The RAOs can be used to estimate the fatigue life. Using the frequency approach proposed by Dirlik [2] an estimation for the damage

rate is proposed. This approach is based on the probability density function (PDF) of tension range for a given sea state environment. The PDF is estimated from a parametric family of densities built from stable distributions of maxima by a moment method [1].

The problem we are facing can be stated as the search for a design $\boldsymbol{x}$ minimizing the material cost $c(\boldsymbol{x})$ while satisfying probabilistic constraints of threshold exceedance type, with a confidence probability level specified by the stakeholders. The idea is to find the least costly design $\boldsymbol{x}$ that satisfies the three probabilistic constraints. The mathematical formulation of the minimization problem is given as follows :

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & c(\boldsymbol{x}), \\ \text{s.t.} \quad & \mathbb{P}_{\boldsymbol{\xi},\rho}\big[\max_{s} g(\boldsymbol{x}, s, \boldsymbol{\xi}) > \rho\big] < 10^{-4}, \\ & \mathbb{P}_{\boldsymbol{\xi},\boldsymbol{X}_{LT}}\left[\min_{s} \inf_{t\in[0,T]} \mathcal{T}(s, t, \boldsymbol{x}, \boldsymbol{\xi}, \boldsymbol{X}_{LT}(t)) < 0\right] < 10^{-4}, \\ & \mathbb{P}_{\boldsymbol{\xi},\boldsymbol{X}_{LT}}\left[\inf_{t\in[0,T]} \beta(t, \boldsymbol{x}, \boldsymbol{\xi}, \boldsymbol{X}_{LT}(t)) < 10\right] < 10^{-4}, \end{aligned} \tag{2}$$

where $\mathcal{T}$ is the tension in the mooring line, β is the angle between the vertical of the floating platform and the mooring line at top extremity and ρ is the random critical value of the accumulated damage that leads to ruin. This level is random, because of uncertainty in resistance to fatigue, which is the material capacity to support cyclic tensions without breaking.

The main difficulty of the problem is the evaluation of the probabilistic damage constraint. First, studies have been done for accumulated damage $g(\boldsymbol{x}, s, \boldsymbol{\xi})$ over period of one year for a fixed design $\boldsymbol{x}$ and fixed values for a damage vector $\boldsymbol{\xi}$. We plan to estimate it by a metamodeling approach. For the two other constraints we plan to adopt the concentration inequalities approach [6].

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