Chance constraint optimization of a complex system - Application to the design of a floating offshore wind turbine

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Abstract:

The problem under interest in this PhD is a Reliability-Based Design Optimization (RBDO) [1] applied to the design of a component of a floating offshore wind turbine. Indeed, the reliability of this structure is in particular insured by the anchoring system of the floating support which restricts the wind turbine motion. This mooring system must have an attractive cost and avoid the ruin caused by a failure of the anchoring lines as a consequence of accumulated damage during the lifespan of the structure. We introduce randomness in the problem by considering uncertainties on the modeling process, represented by the random vector ξ, and on the marine environment conditions, represented by the random process Z. This problem can be mathematically stated as

$$
\begin{array}{ll}
\min\limits_{x\in\Omega} & c(x) \\
\text{s.t} & \mathbb{P}(g(x,\xi) > \rho) < 10^{-4} \\
 & \mathbb{P}(\min_{t\in[0,T]} \mathcal{T}(t,x,\xi;Z) < 0) < 10^{-4} \\
 & \mathbb{P}(\max_{t\in[0,T]} \beta(t,x,\xi;Z) > 6) < 10^{-4}
\end{array}
$$

with :

- x the design variables and $\Omega \subset \mathbb{R}^n$ the feasible set ;
- c the cost of the mooring system ;
- g the fatigue constraint. g has strong non-linearities and is expensive to evaluate ;
- $\mathcal{T}$ the tension of the mooring line ;
- β the constraint on the pitch of the floater (rotation around the vertical axis) that must be less than 6 $^\circ$;
- $Z = (Z(t))_{t\in[0,T]}$ represents the sea elevation and is a locally stationary process that is piecewise stationary over intervals of duration ΔT : $Z(t) = \sum_i \mathbb{1}_{[T_i,T_{i+1}]}(t)\zeta_i(t-T_i)$ where $T_i = i\Delta T$, $(\zeta_i(t))_{t\in[0,\Delta T]}$ are independent stationary Gaussian processes with covariance parameterized by $X_{LT,i}$. $X_{LT,i}$ are i.i.d. random vectors with given discrete joint probability distribution that characterize each stationary sea state.

The calculation of c does not raise any issue. Apart from the judicious choice of the optimization method to obtain an acceptable solution, the difficulty lies in the need to estimate a probability

in the optimization loop. This estimation cost comes from the characteristics of the constraints and the high level of acceptance probability. A naive approach by Crude Monte-Carlo is then prohibited.

We propose a methodology that takes into account the nature of the constraints to reduce the calculation cost.

For the fatigue constraint, there are already methods to deal with the calculation of this type of probability. Methods based on design point (FORM, SORM) require the solving of an optimization problem. Thereby, the RBDO problem becomes a double loop optimization. Different approaches as SORA [2] and SAP [3] have been considered to switch to a single loop optimization problem. We will apply, in a first time, these approaches which will serve as reference results. These methods reduce the computational effort but can lead to incorrect estimate of the probability of failure. Thus, in a second step, we will focus on solving the optimization with the contribution of metamodels coupled with improved Monte-carlo methods [4, 5].

The second and third constraints are evaluated thanks to the Extreme Value Theory [6] to make efficient approximations. Indeed, under some assumptions over a stationary Gaussian process ζ, we have the following result :

$$\mathbb{P}\left(a_T\left(\max_{t\in[0,T]}\zeta(t)-b_T\right)\leq\alpha\right)\to\exp(-e^{-\alpha})\quad\text{as}\quad T\to\infty$$

where a_T depends on T and b_T depends on T and on the second spectral moment of ζ.

The next step will be to add another constraint for the extreme response design which will bring new difficulties due to the high dimension of the uncertainty vector involved.

The methodology is applied to the floating offshore wind turbine used in the benchmark OC4 [7].

References

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Short biography – Alexis Cousin got a Master's Degree from University of Paris-Saclay in modeling and numerical simulation. He is currently a first year PhD student. This thesis, funded by IFPEN, focuses on a Reliability-Based Design Optimization problem applied to the design of an offshore wind turbine.