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Training in Reducing Uncertainty in Structural Safety

Surrogate infill criteria for fatigue reliability analysis of OWT

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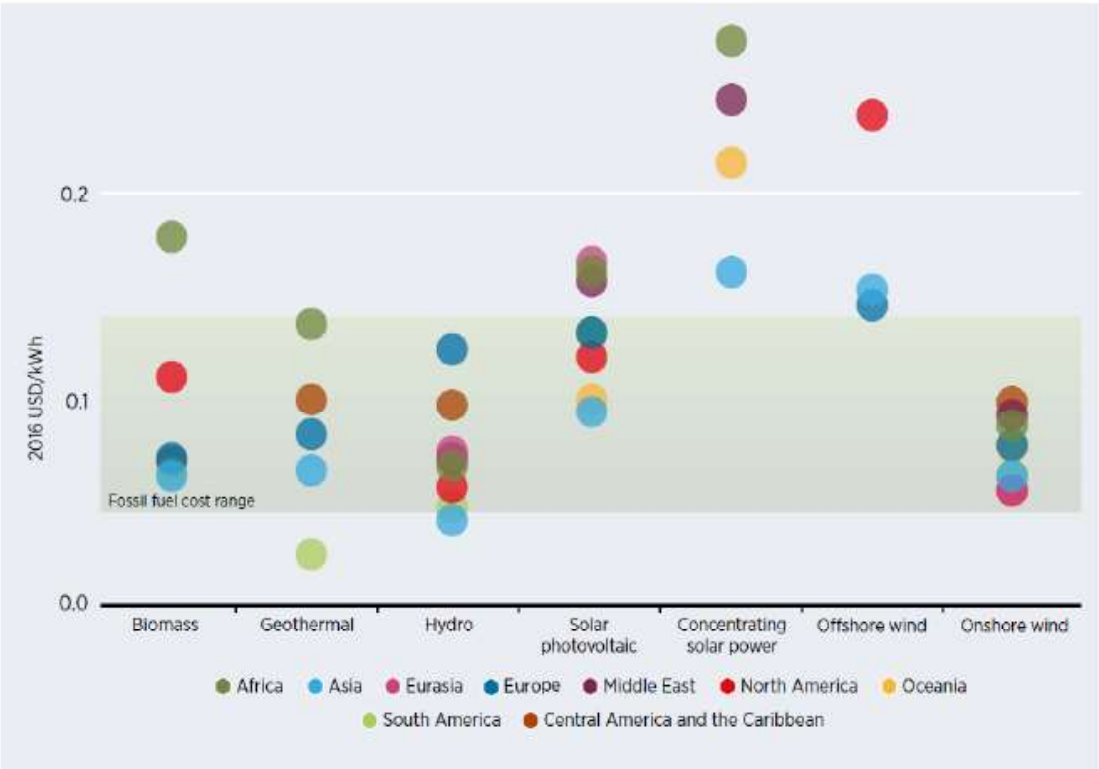
Outline

- Introduction
- Offshore wind Turbine systems
- Stress-cycle (SN) fatigue assessment
- Meta-modelling of SN fatigue
- Search function
- Results and application on a reliability analysis framework

Introduction

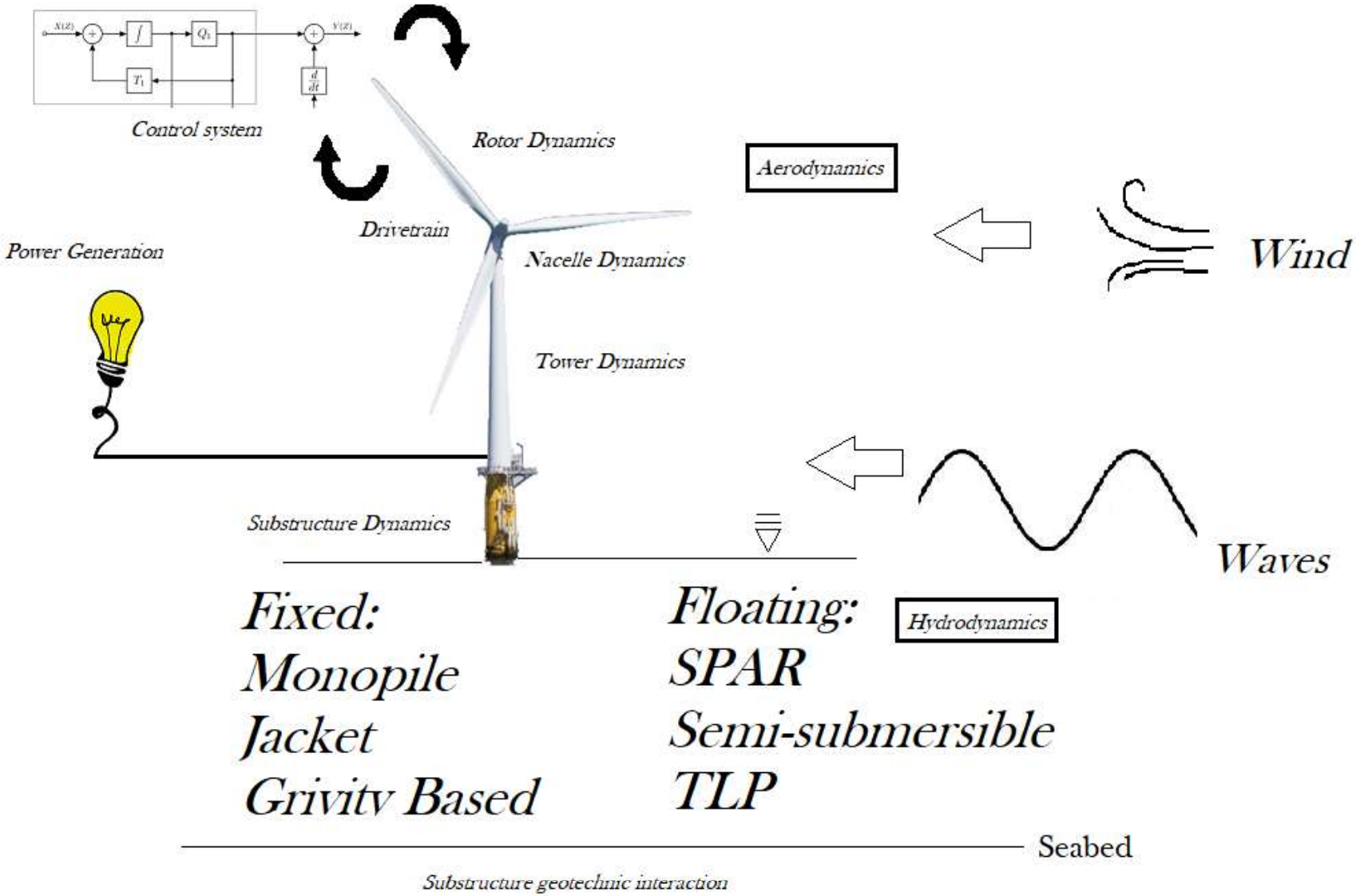
- The demand for renewable energy is unquestionable.
- Innovation in the practices to design and operate Offshore Wind Turbines has been the main key driver to enhance competiveness (IRENA, 2017).
- Research along with regulatory framework are expected to be the main enablers of OWT development up to 2050.
- Scale-up, where the increase of the tower component height has been a major driver of competiveness for OWTs.



Levelized Cost of Energy (LCOE) for different sources of renewable energy divided by region. Source : IRENA 2017 report.

Ref: IRENA. Renewable power generation costs in 2017. Technical report, International Renewable Energy Agency, 2017.

Offshore wind turbine systems



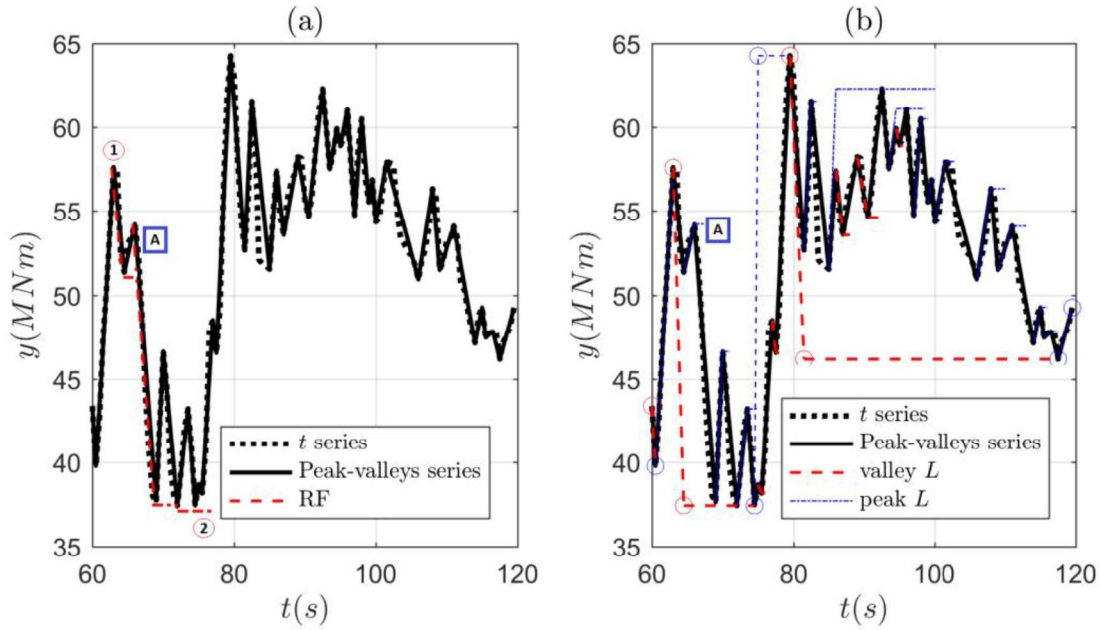
OWT fatigue design

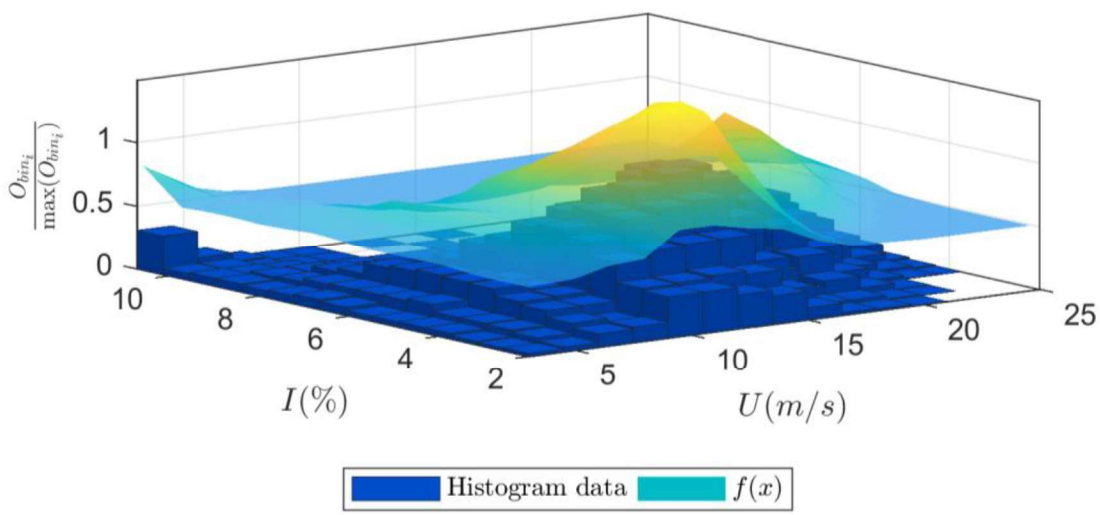
IEC61400 and DNV guidelines.

Run multiple time domain simulations at Θ operational states and count stresses and cycles using counting algorithm (e.g. rainflow counting)

Plus SN curve and:

$$D_T = \sum_{i=1}^{S_n} \frac{n_E(S_i)}{n_{SN}(S_i)}$$





Meta-modelling of SN fatigue

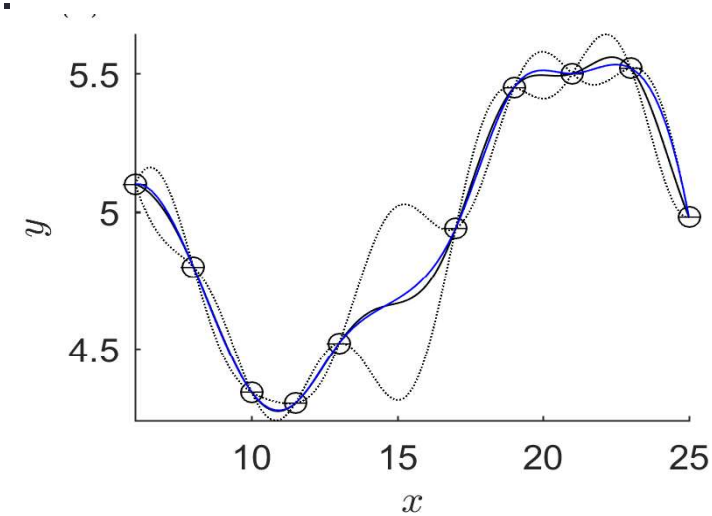
- Gaussian process regression models, or Kriging models, have seen an increase in its application to structural problems.

$$G(x) = f(\boldsymbol{\beta}; x) + Z(x)$$

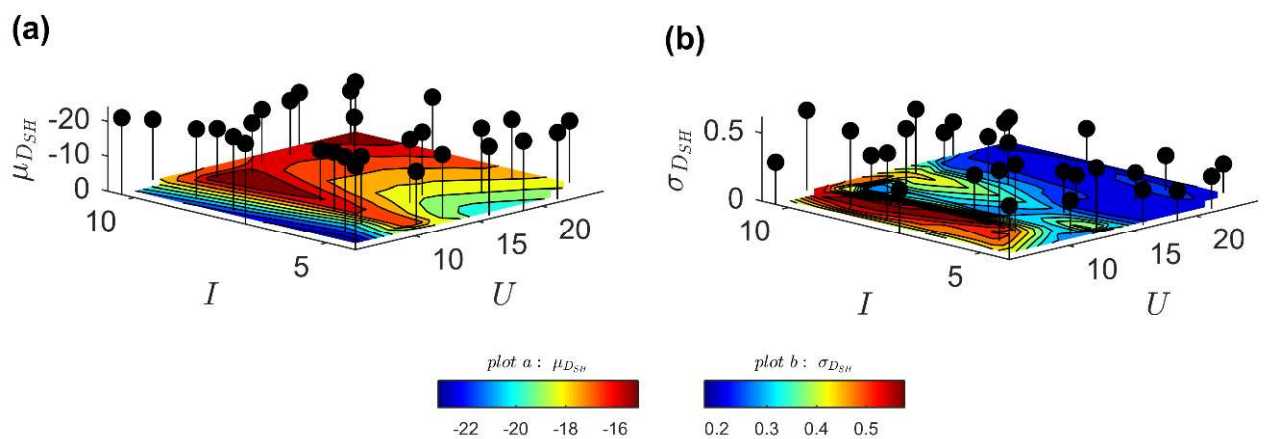
Polynomial Component : $f(\boldsymbol{\beta};\ x) = \beta_1 f_1(x) + \cdots + \beta_p f_p(x)$

$Z(x)$ is Gaussian process with mean 0 and covariance $\boldsymbol{C}$.

$$(x_i, x_j) = \sigma^2 R(x_i, x_j; \boldsymbol{\theta}), i, j = 1 \ldots k.$$

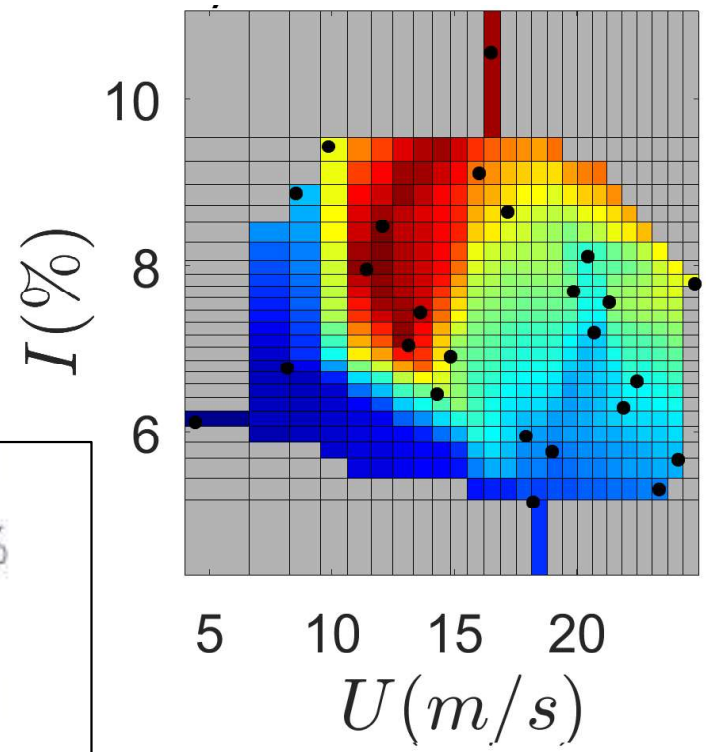


Define a surrogate of short-term SN damage:



LHS DoE Approximation

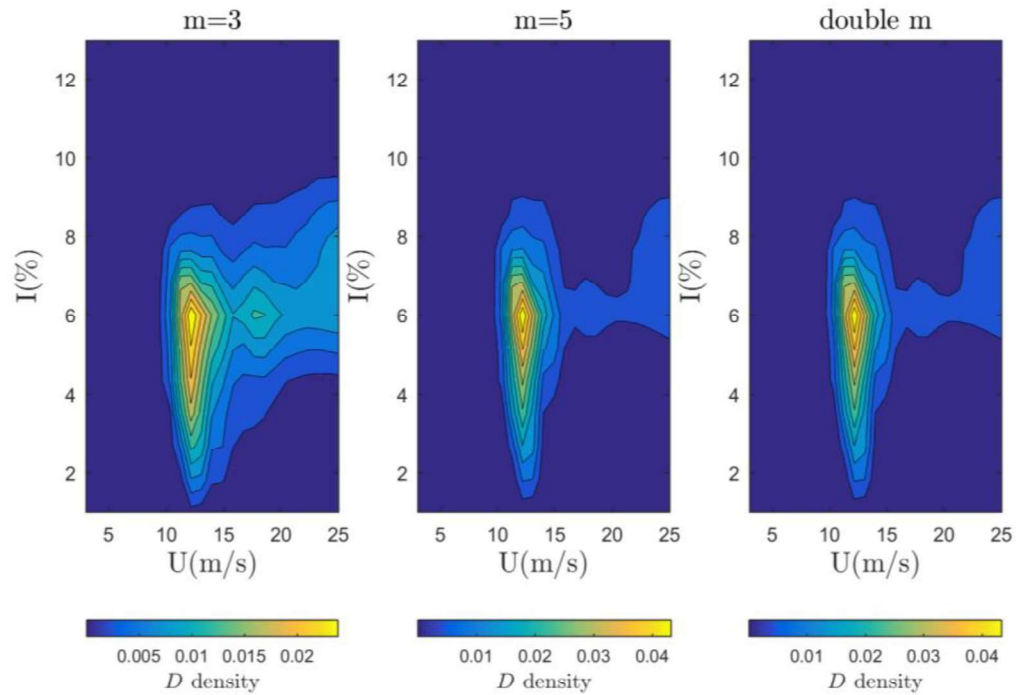
- Common approach in literature works.
- Not consistent.



$m = 5$	I	10 points; correlated	76.5%
	II	10 points; uncorrelated	> 100 %
	III	15 points; correlated	6.6%
	IV	20 points; uncorrelated	23.9%
	V	20 points; correlated	22.4%
	VI	25 points; uncorrelated	> 100%
	VII	25 points; correlated	10.7%
	VIII	30 points; uncorrelated	15.9%
	IX	30 points; correlated	13.8%

Learning criteria

- Kriging enables notion of improvement.
- Relation to the physical problem of fatigue.
- Learning criteria.

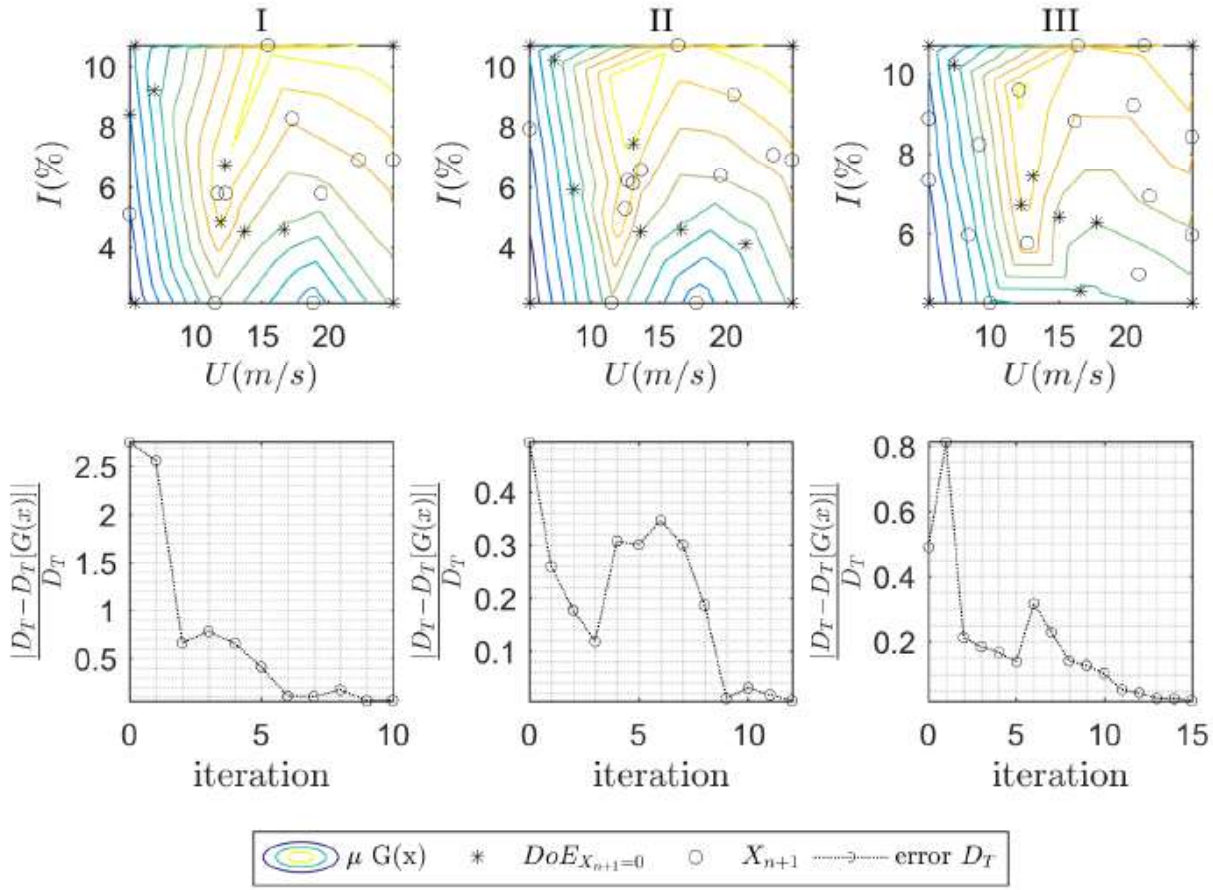


$$\psi(x) = [EI(x) + P_s(x)], \qquad \forall x: \quad 0 < W(x) \leq 1, \quad P_s(x) \in \mathbb{R}^+$$

$$\begin{cases} EI(x) = (min(\mathbf{Y}) - \mu_G(x))\Phi\left(\dfrac{min(\mathbf{Y}) - \mu_G(x)}{\sigma_G(x)}\right) + \sigma_G(x)\phi\left(\dfrac{min(\mathbf{Y}) - \mu_G(x)}{\sigma_G(x)}\right) \\ P_s(x) = \min \mathbf{d}(x|x = x^c): \ \mathbf{d}(x|x = x^c) = \sum_{i=1}^{d} (\mathbf{X}_{ji} - x_i^c)^2, \quad j \in [1, \ldots, k] \ ; \ \forall (x^c) \in x \end{cases}$$

Comparison with standard methodology

- Convergence to the 1 year prediction.
- Robust even when only the corner of the space were given.



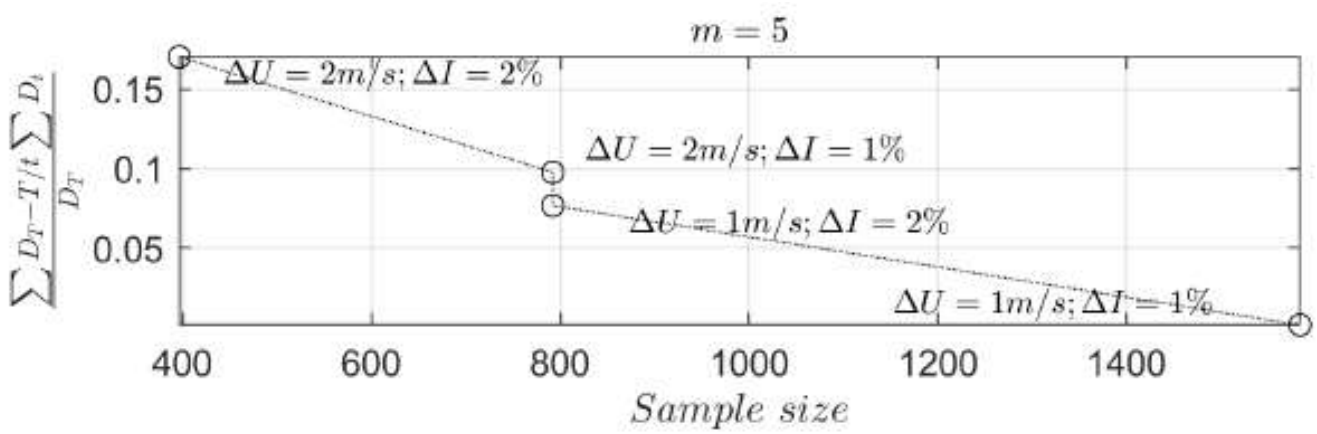
Comparison with standard methodology

Compare with the traditional binning of data.

Reduction of computational time up to 80% without compromising accuracy.

Reduction never inferior to 50% for all the cases studied.

- SN slopes of 3, 5 and double 3 and 5.



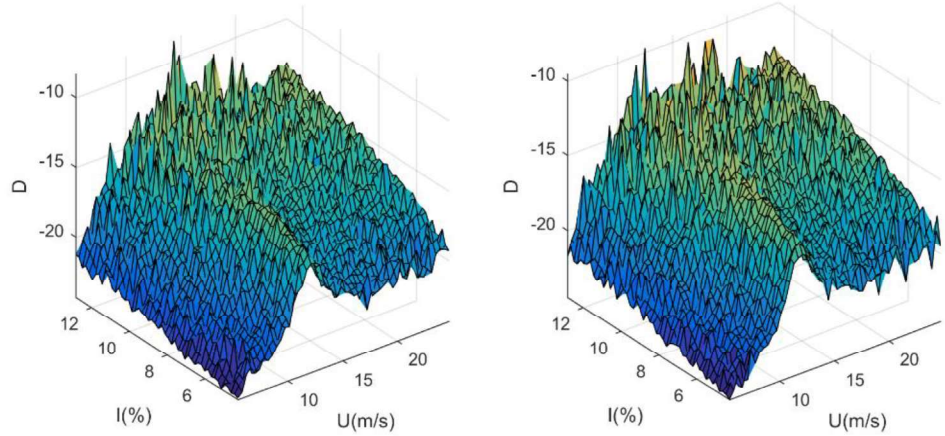
Application for reliability analysis

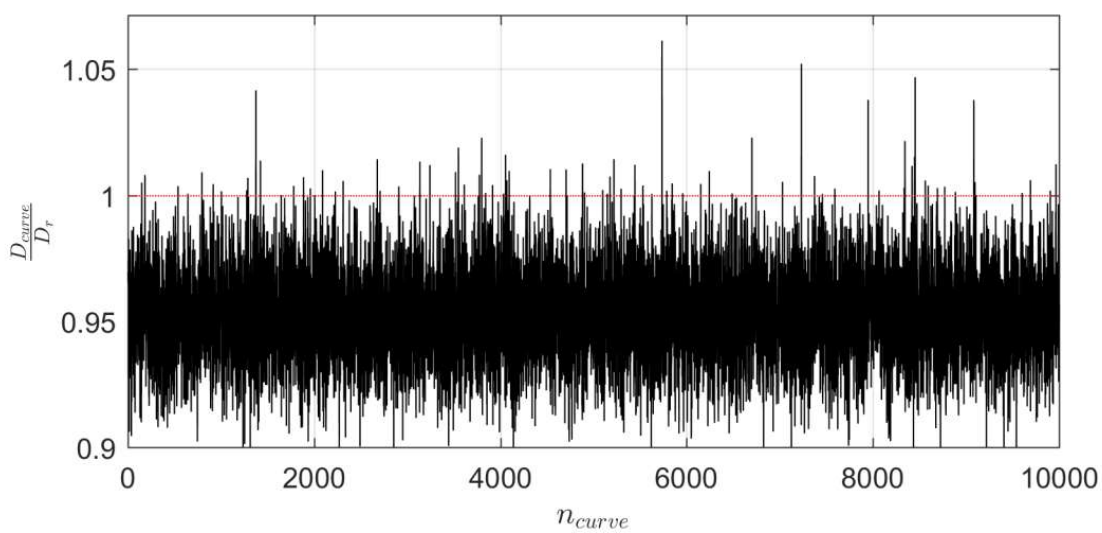
Use the noise component:

$$\boldsymbol{C}(x_i, x_j) = \boldsymbol{C}(x_i, x_j) + \boldsymbol{\delta\tau}^2$$

Allows to define multiple design surfaces. Each one replicates the IEC design assessment.

Distribution of design SN fatigue based on the uncertainty of the design reliability considerations.





Conclusions

- A meta-modelling technique was successfully implemented in order to reduce the computational time of the fatigue design for OWT analysis. It uses a Gaussian process predictor to surrogate the stress-cycle fatigue damage from different operational states.
- It was applied to the tower component, but the same methodology can be extended to any other component.
- The meta-model probabilistic behaviour was of interest to define a “notion” of improvement when approaching SN fatigue.
- In a reliability analysis framework, the main interest is of the surrogate approach presented is the reduction of computational time that may enable reliability based optimization procedures, which challenging to apply for SN fatigue analysis due to their cost.

Thanks for your attention

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