MASCOT-NUM 2022
Clermont Ferrand, France
7-9 June 2022

Adapted line sampling and neural networks for evaluating the info-gap robustness of reliability estimates for penstocks

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PhD expected duration: Nov. 2019 - Nov. 2022

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Abstract:

Structural reliability is of particular interest for risk-sensitive industrial applications such as power generation where system performance, and therefore safety, is subject to uncertainty. In such context, safety is generally assessed by estimating reliability-oriented quantities of interest such as a low probability of failure or a high-order quantile on a specific outcome. In this work, low probabilities of failure are estimated to assess the mechanical integrity of penstocks. However, high-risk systems models are typical cases where epistemic uncertainty can be found. Its impact must be accounted for in order to make an informed decision on the safety of the system. This work uses the info-gap method to evaluate the robustness of the reliability assessment of penstocks to uncertainty affecting the parameters of probabilistic distributions grouped in the vector $\boldsymbol{\theta}$.

The info-gap framework [3] proposes a metric that quantifies the robustness of a quantity of interest to epistemic uncertainty by calculating the worst performance of the model at increasing levels of uncertainty. This approach will privilege a decision that is tolerant to unexpected situations over one that performs better under stronger hypotheses. Its application to reliability quantities of interest such as probabilities of failure has been studied less although an example can be found in [1] in which several epistemic uncertainty representations are compared in term of robustness.

In this work, info-gap robustness curves are drawn by evaluating $\overline{P_\mathrm{f}}(h_i) = \max\limits_{\boldsymbol{\theta}\in U\left(h_i,\widetilde{\boldsymbol{\theta}}\right)} P_\mathrm{f}\left(\boldsymbol{\theta}\right)$ where $U\left(h_i,\widetilde{\boldsymbol{\theta}}\right)$ is a convex set containing the vector of nominal values $\widetilde{\boldsymbol{\theta}}$ that expands with the horizon of uncertainty h_i. Such analysis reduces to evaluating maximum probabilities of failure considering increasing parametric probability box problems. Therefore, a performant probability of failure estimator is required in terms of global precision over the epistemic uncertainty space and in terms of computational time as it involves consecutive optimization problems.

The former requirement is challenging when assessing the reliability of penstocks as the failure event corresponds to a restricted domain defined as a triple intersection of three limit-state functions. To face that, a panel of reliability assessment methods capitalized in the OpenTURNS library-based Persalys-Penstock software already exists. The most efficient method in the context of standard penstock reliability assessments is the so-called FISTARR method [2], an extended adaptation of FORM-Importance Sampling for multiple intersection events. However, the complexity of the limit-state function may lead in some cases to slow convergence.

In order to better target the failure domain, a conditional directional reliability assessment technique named as line sampling [4] is investigated. This method requires to solve multiple one-dimensional reliability problems by evaluating the roots of the limit-state function along lines. However, the specificity of the limit-state function involved in the reliability of penstocks leads to lines that may present no roots

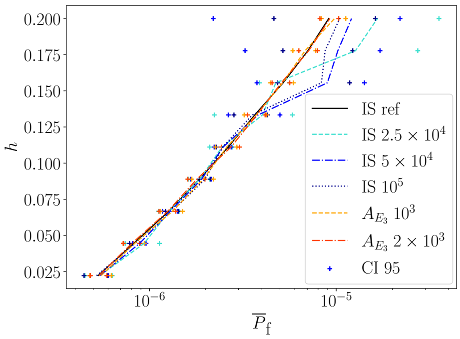

Figure 1: Comparison of robustness curves obtained with the line sampling algorithm A_{E_3} and the IS algorithm.

while others present two roots $r_{1,2}$ which brings to the following probability of failure estimator

$$P_{\mathrm{f}} = \frac{1}{N} \sum_{i=1}^{N} \mathbb{1}_{\{r_{1,2}\}}^{(i)} \left(\Phi \left(-r_1^{(i)} \right) - \Phi \left(-r_2^{(i)} \right) \right) \tag{1}$$

where N is the number of lines, $\Phi(\cdot)$ the cumulative distribution function of the gaussian distribution and $\mathbb{1}_{\{r_{1,2}\}}$ the indicator function that equals to 1 when roots exist and 0 otherwise. Three line-sampling-based algorithms that each corresponds to an equivalent formulation of the intersection failure event are proposed to correctly estimate the existence and the values of both roots at each line search. These algorithms are used for estimating the info-gap robustness curves. Fig. 1 shows a comparison of robustness curves obtained with the FORM-Importance Sampling estimator (denoted as "IS") and one of the three line sampling algorithms A_{E_3}.

Secondly, a novel methodology based on two deep neural networks (DNN) is considered in order to accelerate the prediction of the roots involved in the line sampling algorithms considering the aleatory and epistemic spaces jointly. More specifically, a first classification DNN is built to predict the existence or not of roots for a given line in the joint space. In addition, a second regression DNN is used to estimate the values of the roots when they exist. Finally, the use of a confidence parameter enables to reduce the errors caused by wrong predictions of the first DNN. The proposed methodology considerably reduces the computational burden induced by the info-gap analysis while maintaining a good precision on the predicted robustness curve.

References

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Short biography – This PhD work takes place in the wake of my studies at the engineering school Sigma Clermont where I graduated as mechanical engineer. Through a joint commitment between the electric utility company EDF and the Department of Applied Mechanics, FEMTO-ST, this work aims at developping methodologies for applying the info-gap robustness framework to reliability assessments. This PhD is partially funded by the ANRT.