Statistical analysis of numerical simulations of accidental transients in Pressurized Water Reactors

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Abstract:

In the context of the nuclear industry, Best Estimate (BE) codes are increasingly used [1] in order to optimize the safety margins provided by the analysis of accidental transients, as well as to better understand the complex underlying physics that exist in these simulations. This kind of codes can also provide some insight about the degree of conservatism that is typically adopted in order to ensure the safety of the nuclear power plant.

However, the results provided by BE codes are intrinsically uncertain, which is typically caused by a lack of knowledge of the real phenomena that occur in complex nuclear transients (epistemic uncertainty). This is one of the reasons that justify the employment of statistical tools capable of quantifying the uncertainty associated to the conclusions that are extracted thanks to the information given by the BE codes.

The employment of this kind of codes is in general expensive in time (the simulations may take several hours or days), which considerably hinders their usefulness when taken alone and without making use of complementary tools such as BEPU (Best Estimate Plus Uncertainty) approaches.

Classicaly, this problem is solved by generating a limited number of expensive but accurate BE simulations of the target transient through the design of numerical experiments. Once all the simulations are performed the output data are treated in order to obtain the statistics of interest for nuclear safety, such as extreme values, quantiles etc. This procedure may eventually make use of surrogate models of the code if a larger number of simulations is required, for instance in the context of variance-based Global Sensitivity Analysis [2].

Some of the downsides of this methodology are that, for an essentially physical or engineering problem, the approach that is considered is entirely mathematical, and it usually only takes into account scalar input and output variables, even though the output information is usually richer (such as the temporal evolution of physical parameters of interest during the transient, like cladding temperature, pressure or flow rate.).

In this context, the general objective of this work is to develop statistical tools that help improve the existent black-box approaches, making use of all the information provided by the BE codes. In order to do so, we focus on the outputs generated by a well-known Best Estimate code applied to nuclear transients, the code Cathare2. The output variables that are generated are called functional, i.e., they belong to an infinite-dimensional vector space.

The mathematical formulation of this setting is the following:

$$\boxed{X \in \mathbb{R}^P} \longrightarrow \boxed{\text{CATHARE: } z} \longrightarrow \boxed{z(X) = (z(X,u))_{u\in\mathcal{U}} \in (\mathbb{R}^Q)^{\mathcal{U}}}$$

- (X, z) forms a couple of vectors where the components are random variables (real and functional), with known joint probability law, which models the sources of uncertainty, i.e., $(X(\omega), (z(\omega)) \in \mathbb{R}^P \times \mathbb{R}^Q$ for each event $\omega \in \Omega$.
- For any realization $x \in \mathbb{R}^P$ of X there will be Q variables , $z(x)$, that are functions of a variable u in a spatio-temporal domain $\mathcal{U} \in \mathbb{R}^L$ $(L \leq 4)$. This domain is defined as the cartesian product of a real domain $\mathcal{S} \subset \mathbb{R}^{L-1}$ in the physical space, and a time interval $[0, T]$ such that $\mathcal{U} = \mathcal{S} \times [0, T] : z(x, u) = (z(x))(u) \in \mathbb{R}^Q, \forall u \in \mathcal{U}$.

Assuming that a set of functional outputs from the code is available, the methodology that has been followed consists in developing a novel functional outlier detection [3] [4] technique with the objective of automatically finding the curves that present an anomalous behaviour. This information is useful since the outliers can be representative of non-physical phenomena, which may be caused by simulation errors, as well as particularly certain anomalous scenarios that may provide useful information regarding nuclear safety.

In summary, the main contributions of this work are:

- The development of a new functional outlier detection technique which demonstrates a competitive detection and false positive rate, as well as the capacity of distinguishing magnitude and shape outliers.
- The quantification of the degree of outlyingness of each datum in the analysed set, which facilitates the prioritization of in the physical analysis of the transients.
- The establishment of a technique that allows the quantification of the impact of the input variables in a BE code over the anomalous behaviour of its outputs.

References

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Short biography – I am a second-year PhD student from Madrid, Spain. I have a general engineering bachelor and master's degree from the Universidad Politécnica de Madrid (Spain) and a Nuclear Engineering Master's degree from the CEA Saclay (France). My PhD is related to the nuclear safety field, through a partnership between some the main actors of the French nuclear industry, le CEA — EDF R&D and the Grenoble-Alpes University.