

Epistemic uncertainty-based model validation via interval propagation and parameter calibration

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Highlights

- Interval theory-based analysis framework is established for model validation with epistemic uncertainty.
- An unbiased estimation method is presented for uncertainty characterization.
- Legendre-type polynomial chaos expansion is introduced for uncertain response prediction.
- The concept of interval fitting degree is proposed to establish a new quantitative validation metric.
- Interval parameter calibration is implemented for improving computational accuracy.

Abstract

The model validation with respect to epistemic uncertainty, where only a small amount of experimental data is available, is a challenging problem in practical engineering. Interval theory is a useful tool to deal with such epistemic uncertainty, and this paper aims to construct an interval theory-based analysis framework for model validation. Using the statistical moments of experimental observations, an unbiased estimation method is firstly presented to quantify the interval bounds of system uncertainties. In the subsequent process of predicting uncertain responses, the Legendre polynomial chaos expansion is introduced as the surrogate model, which can greatly improve the computational efficiency of uncertainty propagation. Then the concept of interval fitting degree is proposed to establish a new quantitative validation metric, which can accurately characterize the agreement between the computational response interval and experimental response interval. Meanwhile, an operation of interval parameter calibration is executed in the form of optimization to improve the prediction accuracy of computational model. Finally, the Sandia thermal challenge problem is utilized to verify the feasibility of presented model validation method in engineering application.

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Keywords: Model validation; Epistemic uncertainty with limited data; Interval theory; Polynomial chaos expansion; Interval fitting degree; Interval parameter calibration

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1. Introduction

In practical engineering, the experimental tests and computational simulations are the two important means for system analysis. The large number of experimental tests can obtain the intuitive and reliable results, but the experimental cost is relatively high, especially for the complex systems. With rapid development of computer technology, the computational simulations become more and more popular due to the relatively small cost. However, before the practical application, it is necessary to assess the predictive capability of a computational model [1–3]. Model validation, defined as *the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model* [4], is just the general technique to assess the simulation credibility.

As is known to all, uncertainties related to the unpredictable environment factors, inevitable measurement errors, incomplete knowledge, etc. widely exist in the real world [5–9]. With intensive requirement for system exactitude design, quantifying and evaluating various uncertainties have become imperative. In recent years, the model validation under uncertainty analysis framework has received considerable attentions from many scientific societies and laboratories [10,11]. The American Institute of Aeronautics and Astronautics (AIAA) and the American Society of Mechanical Engineers (ASME) have published the guidance documents for promoting model validation in computational fluid dynamics and computational solid mechanics [4,12]. The U.S. Department of Energy emphasized the importance of uncertainty-based model validation in the Accelerated Strategic Computing Initiative (ASCI) program plan [13].

Generally speaking, based on the difference between present state of knowledge and complete knowledge, the uncertain factors can be classified into two categories: aleatory uncertainty and epistemic uncertainty [14]. Using the sufficient information, the aleatory uncertainty is usually quantified as random variable or stochastic process by probability theory. Up to now, a lot of investigations have been conducted on the aleatory uncertainty-based model validation [15–19]. Based on abundant experimental data, Hills and Trucano constructed a statistical validation model, where the statistical inference theory was utilized to test the model predictions against experimental observations [20]. By using random variables to quantify uncertainties caused by the measurement errors and spatial heterogeneity, Luis and McLaughlin proposed a stochastic approach for model validation, which could identify the model deficiencies based on objective standards for model performance [21]. Besides, for the three famous challenge problems proposed by Sandia National Laboratories, a lot of research results have been obtained in the probabilistic framework [22–26]. However, when the available data are scarce, the probability theory becomes not so useful, because the needed probability distribution functions cannot be accurately constructed by the limited information. Comparatively speaking, the epistemic uncertainty is more suitable to address the problem without complete knowledge [27], and the epistemic uncertainty-based model validation is receiving widespread concern [28,29].

Several quantification methods, such as fuzzy set [30], evidence variable [31] and interval theory [32], have been adopted to describe epistemic uncertainty. The fuzzy set-based model validation problem has been investigated by several scholars [33,34], where the fuzzy variables were usually transformed into a group of interval variables under the cut-level operation. Based on the evidence theory, Deng et al. proposed an evidential model validation method, where the frame of discernment of evidence variable was determined by Bayesian hypothesis testing and Bayes factor [35]. However, in both fuzzy and evidence frameworks, additional expert knowledge was still required in advance to construct the membership functions and basic probability assignment of uncertain factors. Relatively speaking, the interval theory can be considered as the simplest and most practical method for epistemic uncertainty quantification [36–39]. First, interval theory is an extension of classical probability theory, and it utilizes an interval range to characterize the uncertainty fluctuation, which is more convenient to dispose the incomplete information with limited data. Besides, the concept of interval variable can be flexibly adopted to define the basic elements of other uncertainty models, which means the interval theory has great application potential in a more complex environment with mixed uncertainties. In recent years, the imprecise probabilistic methods, where the interval theory and probability theory are combined, have been proposed to solve the model validation problem with mixed epistemic and aleatory uncertainties [28,40,41]. By treating probability distributional characteristics as interval numbers, Ferson et al. proposed a novel validation method to assess the overall predictive capability of computational model [42]. In spite of above important progresses, the research about interval theory-based model validation is still in the preliminary stage, where several issues such as interval validation metric, parameter calibration, etc. have not been well addressed.

In this study, a novel interval theory-based model validation method is proposed to assess the simulation credibility of computational model with epistemic uncertainty. According to the general flow diagram of model validation

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