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Quantifying uncertainty in parameter estimates of ultrasonic inspection system using Bayesian computational framework

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ABSTRACT

This paper will aim to characterise statistically the uncertain parameters in an ultrasonic (UT) inspection system from limited signal measurements and prior information in order to enhance the confidence on the probability of detection (POD) curve. The POD curve is widely used in industry to quantify the capability of a non-destructive testing technique to detect a defect with a given specifications. A realistic estimation of the POD requires to consider the uncertainty in the input parameters. However, in practice the uncertainties are seldom well quantified, which may cause problems for the POD estimation and its reliability to qualify robustly an inspection system. To address this issue, one proposes to characterise the uncertain parameters based on the information content in the UT signal. One of its distinctive features which can be used to solve the challenging inverse problem is the amplitude of the signal. A Bayesian approach seems a convenient framework for coping with limited number of measurements and prior information from experts' judgement to keep POD cost as low as possible. An illustration which consists to control a tube with an embedded defect is provided to demonstrate the efficiency of the proposed methodology to quantify uncertainty in the input parameters. The *nested sampling* (NS) algorithm is used to make Bayesian inference for an efficient exploration of the posterior space. To reduce the computational requirements, the UT physical model is replaced by an emulator based on the least square support vector machines method. The obtained results show that by combining a limited number of measurements with priors may be a promising way to characterise statistically the uncertain parameters within reasonable computational time and acceptable accuracy. The study is carried out numerically by exploiting synthetic data generated from an UT physical model.

1. Introduction

Uncertainty quantification (UQ) and propagation is becoming of central importance in many engineering areas to better control and enhance the reliability and robustness of mechanical systems, structures and processes [1–7]. Controlling the structural health of aircraft, nuclear reactor components and pipelines using non-destructive testing (NDT) methods (e.g., UT, eddy-current testing, X-ray radiography, ...) is a typical problem where different sources of uncertainty exist and should be considered. To qualify and measure the performance of an inspection system to detect a specific defect is one of the

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engineering problems where one needs to properly quantify and propagate the uncertainty to estimate the POD curve. The POD is the most commonly used measure of NDT performance. To be more specific, the POD curve gives a measure of the performance of a NDT method to detect a defect with a given specifications. The estimation of the POD curve requires the knowledge of the probability density function (PDF) associated to each of the uncertain parameters to be effective and useful. However, in practice it is very difficult to assign arbitrarily a statistical distribution to a random parameter in an inspection system. To circumvent this issue, a Bayesian approach which combines information from the signal and a priori knowledge is proposed to estimate the unknown statistical distribution. Although, the problem can be stated simply, it is not at all easy to solve for many reasons; it is actually an inverse problem and can be extremely ill-posed. The solution of an ill-posed problem is generally non-unique and often unstable. In addition, the available measurements is always limited in number owing to either financial or technical constraints.

Before, one starts to discuss the various UQ methods proposed in the literature, the main sources of uncertainty present in an inspection operation is firstly introduced. In non-destructive inspection (NDI) techniques, uncertainty may come from the part to be inspected (material properties, geometry, surface roughness, . . .), defect properties (length, width, tilt angle, . . .) and the inspection process itself (probe position, electronic devices, scan plan, . . .). There will be additional variability associated with setup procedures, e.g., the inspector's ability to reproducibly align the probes for instance. In practice, it is very difficult to characterise statistically the variabilities associated to the physical uncertain parameters and more for human error and then associate a suitable distribution density for each parameter. In most cases and in order to simplify the problem, a parametric description is given in terms of intervals defined by subject matter experts and/or by very limited information but not full probability distributions. Moreover, in NDI problems, sometimes the structure of the distribution is not well known and in the absence of a physical justification (positive definiteness for instance), it is not possible to assign arbitrarily a standard statistical distribution to represent the uncertainty. The knowledge of density distributions allows us to properly propagate the uncertainty and then enhance the confidence in the POD curve. One of the objectives of this paper is to provide a precise characterisation of the uncertain parameters to get more accurate POD curve. To reach this objective, a Bayesian inversion scheme is proposed to quantify the uncertainty based on the information in the signal and a priori knowledge from experts. In the present study, the amplitude of the signal is used as the main feature to make Bayesian inference. Fig. 1 presents a flowchart of the proposed methodology. It is composed of two steps: Step 1, consists in characterising the unknown parameters involved in an UT inspection system from probabilistic viewpoint based on a set of available data from the UT signal and information from experts. Then, in Step 2, one propagates the uncertainty in the input parameters using the UT model to get the POD curve.

During the last decade, several methods have been proposed in the literature to quantify the uncertainty and the choice of the convenient one depends on the problem at hand and the available data. Among the proposed computational tools for performing UQ include stochastic algorithms such as Markov Chain Monte Carlo (MCMC) and its variants; the Delayed Rejection Adaptive Metropolis (DRAM) [8] and Transitional Markov Chain Monte Carlo (TMCMC) [9–11]. In addition to these methods, non-sampling stochastic techniques have been proposed to produce functional representations of stochastic variability. The generalised polynomial chaos (gPC) expansion plays major role in these methods therewith uncertain parameters and structure responses can be characterised by linear combination of random orthogonal bases [12,13]. The method has

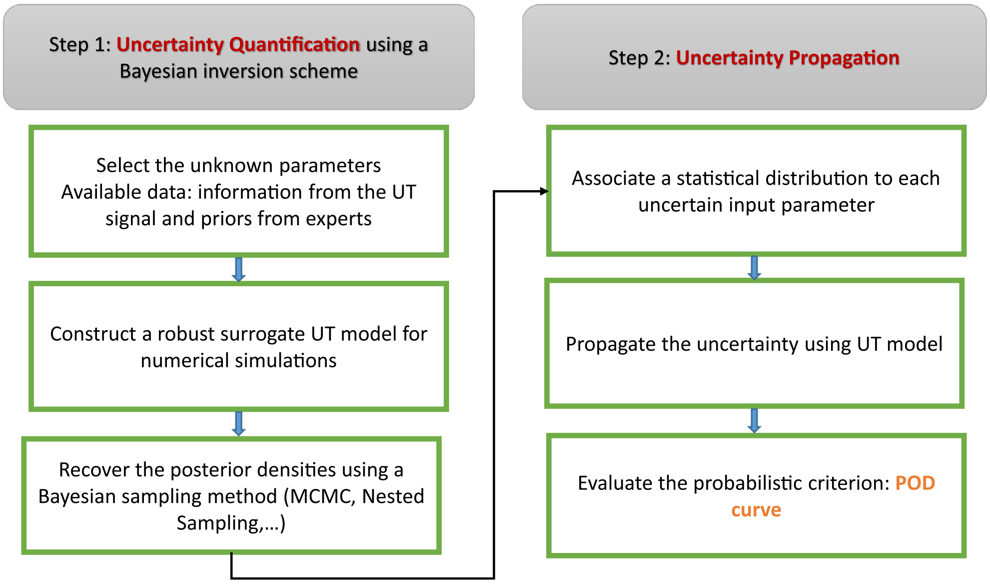

Fig. 1. A flowchart of the proposed methodology.