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On-line Bayesian model updating for structural health monitoring

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ABSTRACT

Fatigue induced cracks is a dangerous failure mechanism which affects mechanical components subject to alternating load cycles. System health monitoring should be adopted to identify cracks which can jeopardise the structure. Real-time damage detection may fail in the identification of the cracks due to different sources of uncertainty which have been poorly assessed or even fully neglected. In this paper, a novel efficient and robust procedure is used for the detection of cracks locations and lengths in mechanical components. A Bayesian model updating framework is employed, which allows accounting for relevant sources of uncertainty. The idea underpinning the approach is to identify the most probable crack consistent with the experimental measurements. To tackle the computational cost of the Bayesian approach an emulator is adopted for replacing the computationally costly Finite Element model. To improve the overall robustness of the procedure, different numerical likelihoods, measurement noises and imprecision in the value of model parameters are analysed and their effects quantified. The accuracy of the stochastic updating and the efficiency of the numerical procedure are discussed. An experimental aluminium frame and on a numerical model of a typical car suspension arm are used to demonstrate the applicability of the approach.

1. Introduction

The fatigue weakening is affecting mechanical components subject to alternating load cycles. Intermittent load cycles can initiate cracks which propagate through the cross section of the structures. In particular, interactions may occur between the structural responses and cracks in components subject to high-frequency dynamic excitations, leading to vibration-induced fatigue. Once a critical crack length is exceeded, the structure will catastrophically and suddenly fail, even for a stress level much lower than the design stress [1]. Consequences may be a premature failure of the component or, even worst, the loss of the entire structure which relies on the component integrity. Several strategies are accountable to prevent sudden failures. For instance, non-destructive inspections may be performed at predetermined time intervals in order to detect the cracks [2]; however, failure may occur between intervals [3]. Alternatively, a continuous (on-line) monitoring of the dynamic response of the structure can allow for real-time crack detection and for a timely intervention with maintenance procedures

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[4]. Repair actions are taken in case the monitoring procedure successfully identifies cracks which may jeopardise the structure.

In literature, a number of research has been published proposing damage identification procedures, e.g. [5–11]. Part of those studies dealt with real-time or quasi-real-time crack detections but, unfortunately, just few explicitly accounted for relevant sources of uncertainty. J. Maljaars et al. [5] proposed a Bayesian framework for fatigue life updating accounting for inspection an uncertainties. Refs. [6–9] developed methods for real-time damage detection based on different device response signals (e.g. acoustic resonance analysis or device thermography), however, uncertainty has been just implicitly accounted or fully neglected. Recently, Baraldi, Compare, Turati, Mangili and Zio [10,11] assessed the health status and remain useful life of components considering uncertainty and employing an efficient particle filtering method. Generally speaking, uncertainty is inevitable and can be due to endogenous factors, e.g device parameters and model discrepancies, or to external exogenous factors, such as environment variability and measurement noises. To the authors viewpoint improve reliability and robustness of health monitoring approaches is uttermost important and to produce superior methods, further research has to be produced explicitly accounting for uncertainty.

Uncertainty in crack detection and damage identification problems arises from a variety of sources; it can affect the numerical model of the device, which differ from the real component due to e.g. variability in the manufacturing procedure. It can also affect the measured data, due to inadequate measurement devices, noises of surrounding environment or due to a lack of abundance in measurements. Fatigue failures have proven to have an inherent random behaviour [12], which further highlight the necessity of considering uncertainties if aiming at improving crack detection procedures. Popular emerging techniques are now available in the field of computational mechanics, which can be employed to assist in the monitoring of the health of the structures. These techniques modify some specific parameters in a numerical model to ensure a good agreement with the data, a so-called inverse problem. A computational framework well-suited for the solution of such inverse problems also accounting for relevant uncertainties is the stochastic model updating [13–20].

Authors in Ref. [17] proposed a Bayesian updating approach for fatigue damage prognosis employing the so-called reversible jump Markov chain Monte Carlo. The framework can account for uncertainties and two simple crack growth model were analysed. However, computational time issues typical of these type of frameworks were not explicitly discussed. Similarly, the Authors in [18] proposed a Bayesian updating method for crack size quantification and using Lamb wave signals. The method was effective for damage prediction but problems of efficiency are not mentioned. H. Sun et al. [19] proposed an updating framework for multi flaws identification, based on extended finite element method and adapting artificial bee colony algorithm. A parametric study of the noise uncertainty was also proposed. The computational time was an issue and the author briefly discuss a hypothetical solution which consists in run the analysis in parallel on a compute cluster. In reference [20], the authors present a stochastic updating framework and discuss problems of imprecise probability. Imprecise probability becomes relevant for situation where available data are not abundant and information scarce, vague or inconsistent. In those situations, hard to justify artificial assumptions may be needed to define a probabilistic model and characterise uncertainty (e.g. to define a probability distribution with no information on the family and just few specimens). Advanced methods to model uncertainty have been specifically proposed, which permit to perform analysis using less and weaker assumptions and quantifying the extent of the imprecision. For instance, some of the most widely employed mathematical tools to deal with imprecision are intervals, probability boxes, Dempster-Shafer structures, possibility distribution and fuzzy variables [20,21]. The vast majority of the reviewed works did not account for efficiency in the computations at the same time providing an indicator of the imprecision surrounding the analysis. Furthermore, none of the reviewed papers assessed the robustness of the Bayesian updating procedure with respect to different likelihood functional expressions.

In this work, a Bayesian stochastic updating framework is proposed to efficiently tackle two damage identification problems. The feasibility of the procedure when real experimental data are employed is tested using a real-life aluminium frame [22]. The frame's natural frequencies are measured and used as experimental data in the procedure. A second application tests the cracks detection procedure using a numerical car suspension arm [23]. The mechanical behaviour of device is characterised by collecting synthetic Frequency Response Functions (FRF) at a specific location and sources of aleatory and epistemic uncertainty have been analysed and their effect quantified. Measurement noises, numerical model discrepancies and an increasing lack of knowledge about the true crack parameters are explored and presented in the paper. Two representative crack detection cases of increasing complexity are analysed; first, the detection of a single crack of known position and not known length, secondly, the detection of a single crack of not-known position and not known length. Likelihood functions are used in any Bayesian updating procedure to compare the experimental observations and the model [14–16,24,25]. Different mathematical formulations can improve accuracy and robustness of updating procedure. Hence, different numerical likelihoods are proposed in order to encode differently the experimental evidence in the procedure. Furthermore, interval-valued indicators are proposed to quantify the level of imprecision in the damage detection based on the 5^{th}–95^{th} percentiles credibility interval.

Computational efficiency is an hard requirement for real-time applications and by including uncertainty, the problem worsens. Specifically, many time-consuming model evaluations are required for the uncertainty quantification. This issue has been faced by adopting an emulator. In theory different emulator types can be used if adequately trained to reproduce the model input–output relationship. In this work, Artificial Neural Networks (ANN) [25] because they are flexible, in principle, universal approximating functions able to deal with non-linearity. In addition, a parallel computing strategy is adopted