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Iterative structural identification framework for evaluation of existing structures

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ABSTRACT

Evaluation of aging infrastructure has been a world-wide concern for decades due to its economic, ecological and societal importance. Existing structures usually have large amounts of unknown reserve capacity that may be evaluated though structural identification in order to avoid unnecessary expenses related to the repair, retrofit and replacement. However, current structural identification techniques that take advantage of measurement data to infer unknown properties of physics-based models fail to provide robust strategies to accommodate systematic errors that are induced by model simplifications and omissions. In addition, behavior diagnosis is an ill-defined task that requires iterative acquisition of knowledge necessary for exploring possible model classes of behaviors. This aspect is also lacking in current structural identification frameworks. This paper proposes a new iterative framework for structural identification of complex aging structures based on model falsification and knowledge-based reasoning. This approach is suitable for ill-defined tasks such as structural identification where information is obtained gradually through data interpretation and in situ inspection. The study of a full-scale existing bridge in Wayne, New Jersey (USA) confirms that this framework is able to support structural identification through combining engineering judgment with on-site measurements and is robust with respect to effects of systematic uncertainties. In addition, it is shown that the iterative structural-identification framework is able to explore the compatibility of several model classes by model-class falsification, thereby helping to provide robust diagnosis and prognosis.

1. Introduction

Due to conservative strategies that are fueled by high risks associated with the construction of large civil structures, most structures today have significant amounts of unknown reserve capacity. In the context of structural health management of existing aging structures, structural identification is attractive for decision-making support. The goal of model-based data interpretation is to increase the knowledge of real behavior of complex structures using information provided by behavior measurements. In order to interpret measurement data, physics-based models are used to connect hypotheses of structural behavior to observed behavior and to identify uncertain parameter values of physical properties. This interpretation serves to improve behavior diagnosis and reduce uncertainties associated with behavior prognoses, such as remaining-fatigue-life evaluation. However, diagnosis is an ill-defined task that is performed under conditions of high modeling and measurement uncertainty. In addition, modeling errors are usually systematic, also called epistemic errors as opposed to random errors, thereby increasing interpretation difficulty.

Single-model-updating approaches such as residual minimization have already shown to be inaccurate in the presence of systematic errors since a single optimal model is intrinsically imperfect due to parameter-value compensation [1–4]. Instead, there are always multiple models that are able to explain observations of the behavior of complex structures. Approaches such as probabilistic Bayesian inference accounts for multiple solutions through updating posterior probabilities of parameter values, thereby estimating the uncertainty associated with the parameter values. However, a common assumption in these approaches is that modeling and measurement errors are adequately described by a joint independent zero-mean Gaussian probability density function (PDF) [5–7], which is incompatible with the systematic nature of several modeling uncertainty sources. In addition, some applications incorporate the variance of the joint PDF as a parameter in the identification process [8–10] and others assign

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an arbitrary value to the variance [11–13]. However, in complex civil structures, modeling uncertainties are often biased and correlated spatially. In addition, defining a statistical model of errors that is not compatible with the true errors leads to biased diagnostics and prognosis [3,14]. While Bayesian inference may provide useful support when statistical models of errors are known, it is not robust when aspects such as correlations cannot be quantified.

For the purposes of this paper a model class is defined as a parameterized physics-based model, where parameters are variables whose values need to be identified. Models are instances of model classes. In the context of Bayesian inference, proposals exist to select an optimal model class among a set of possible model classes that gives the best trade-off between data fitting and model-class complexity in order to solve diagnosis and prognosis tasks [9,15–17]. Some approaches link to Ockham's razor [18,17], also called principle of parsimony, which asserts that simpler models that are compatible with measurements are preferred over complicated ones. However, simpler models may imply over-idealization of reality and consequently modeling uncertainties. Despite undeniable benefits of this principle to simplify modeling and data-interpretation tasks, the question of the presence of systematic errors in the model class has not been treated explicitly. Although several authors in various fields have pointed out the importance of providing an adequate description of modeling uncertainties associated with the model class [4,19–22], proposals for robust alternatives to existing approaches are lacking.

Goulet and Smith [3] proposed an approach that is robust when knowledge of the joint PDF of modeling and measurement errors is incomplete. This approach, named error-domain model falsification (EDMF), combines PDFs of each source of modeling and measurement error and determines conservative probabilistic thresholds that are used to falsify inadequate models. Modeling errors are estimated using engineering heuristics and field observations. They have shown that this approach leads to robust parameter identification in the presence of systematic errors without precise knowledge of the dependencies between modeling errors. Goulet and Smith [3] also demonstrated that the assumption of independence in the common definition of uncertainties in Bayesian inference may bias the posterior distribution of parameter values in the presence of systematic errors. This last observation has also been noted by Simoen et al. [23]. Although Goulet and Smith [3] have observed that EDMF can reveal situations when initial assumptions related to the model class are erroneous by falsifying all model instances, taking advantage of this characteristic for exploring possible model classes of complex structures has not been studied.

Choi and Beven [24] have also observed that model falsification could serve to point out model deficiencies in the search for a better model class. This observation resulted in the proposal of the generalized likelihood uncertainty estimation (GLUE) framework [25] in the field of environmental modeling, which is also affected by large modeling uncertainties. Other examples of model-falsification procedures can be found in this field. Beck [26] presented a framework for analysis of uncertainty and model selection based on recursive search and model discrimination. An approach, called Monte Carlo filtering, is used for discarding sets of inadequate model instances. Also, in the field of geology, Cherpeau et al. [27] proposed a fault-scenario falsification approach using a misfit threshold. However in such examples, systematic errors were not included explicitly.

In the field of civil engineering, structural identification processes are often based on residual minimization approaches [28–31], which may lead to biased results in the presence of unexpected systematic modeling errors. Moon and Aktan [32] proposed a structural identification framework composed of six steps for diagnosis and prognosis of complex structures. The process starts with the observation and conceptualization (step 1) of the structure from which an a priori model is developed in order to design in situ experiments. The data collected is then processed and used to identify the system for subsequent prediction by simulation (step 6). In spite of the original intention by Moon and Aktan [32] for step 6 to iterate back to step 1, this methodology does not fully reflect the iterative aspect of data interpretation. Practice has shown that, prior to interpreting measurements, engineers may not fully understand all possible model classes of structural behavior. For complex structures, a multi-stage backtracking procedure is often required because the diagnosis task is an exploratory process involving several iterations [33] of observation and measurements, data interpretation, modeling and performance predictions.

This paper presents a new structural identification framework based on an iterative falsification process and knowledge-based reasoning. This framework is illustrated for the structural identification of a complex bridge structure where several uncertainties related to the structural behavior prevents single pass identification. It is demonstrated that the iterative structural identification framework is able to explore compatibility of several model classes of the structure by falsifying inadequate model classes. Thus, this approach is able to make diagnosis and prognosis of the structural conditions using engineering heuristics and on-site measurements, and is robust to modeling systematic uncertainties.

Section 2 describes the iterative structural identification framework along with the tasks to be performed. Section 3 presents the steps of the framework applied to a full-scale bridge and a discussion of the resulting diagnosis. Finally, Section 4 contains a summary and discussion of the iterative aspects and future work.

2. Iterative structural identification framework

Structural behavior diagnosis is an ill-defined inverse engineering task that is carried out in open-world conditions and thus, under much uncertainty. For these reasons, such tasks usually lead to multiple explanations for the structural health management of existing structures. The number of possible explanations may be reduced by acquiring knowledge of the structural behavior. The experience and judgment of the engineer as well as other forms of heuristic knowledge are thus of utmost importance. In the field of knowledge-based reasoning, knowledge is acquired by new information obtained using data-interpretation tools [34]. Through these tools, engineers may test their knowledge and their hypotheses against observations.

Diagnosis tasks are usually solved through a process of hypothesis generation and testing. Hypotheses are generated at an early stage from a basic knowledge acquired from limited information. While an early-stage hypothesis may be revised or discarded if subsequent data fail to confirm it, it is likely that at least some hypotheses are correct. Hypotheses are used to organize engineering knowledge and they help to reduce the size of diagnosis task search space. Because it would not be possible to guide an efficient diagnosis task without some hypothetical purpose, hypotheses serve to transform an open-world ill-defined task into a set of well-defined deductive tasks. This process is done iteratively while gradually acquiring knowledge from new observations and from rejected hypotheses.

In this context, the structural identification framework is governed by the principle of falsification, which has been well known by scientists for centuries. However, this principle has only been popularized in the 1930's by Popper [35]. His philosophy stipulates that hypotheses cannot be fully validated by observations and rather can only be falsified by observations. Several authors, such as Tarantola [36,37] and Beven [26], underlined the advantages of this philosophy since it avoids biasing observations by hypotheses.