Computers and Structures 196 (2018) 49–62

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Structural response predictions compared to material property estimates for structural integrity assessment under operational uncertainty

Kyunghoon Lee

Pusan National University, Busan 46241, Republic of Korea

ARTICLE INFO

Article history:
Received 2 May 2017
Accepted 18 October 2017

Keywords:
Structural integrity assessment
Operational uncertainties
Bayesian inference
Certified reduced basis methods

ABSTRACT

To examine structural integrity in consideration of operational uncertainties, we utilized structural response predictions obtained by transmitting estimates of structural system parameters into a simulation representing the actual system. For this purpose, we resolved inverse parameter estimation by Bayesian inference and constructed a forward model using certified reduced basis methods. For demonstration, we applied the proposed assessment strategy to two isotropic structural systems under static, linear elastic deformation: a beam and a plate subject to bending and shearing dominant loadings, respectively. Numerical investigation with emulated damage cases showed that structural response predictions were superior to material property estimates for inspecting structural integrity, particularly when operational uncertainties were not ignorable.

1. Introduction

By virtue of sensor technology progress enabling sensor-attached/-embedded structures [1], in situ, real-time sensor readings are available for numerous applications in the context of structural health monitoring and control [2]. In the literature, structural integrity has been assessed via structural parameters estimated in the form of system identification [3–13]. For instance, various structural responses—such as displacements, strains, natural frequencies, and modal shapes—have been employed for tracking diverse structural parameters—such as material properties, stiffness, mass, and damping coefficients. In general, system identification can be tackled by either a deterministic or a probabilistic approach. The former seeks to find parameters that minimize misfits between measured and predicted structural responses, whereas the latter with the Bayesian perspective looks for parameters that maximize the posterior probability of the parameters given measurements [14–18]. Either way, system identification mainly concerning material properties tends to presume that operational conditions are precisely known *a priori*. However, information on operational conditions may not be dependable in practice due to noise contamination or poor measurability. Consequently, uncertain operational conditions may adversely affect material property estimation, which subsequently results in misleading damage assessment.

Continuing with the previous research [19], we utilized structural response predictions in lieu of material property estimates to enhance structural integrity assessment in the following fashion: (i) solved an inverse problem to indirectly determine unobservable material properties as well as uncertain operational conditions; (ii) propagated the estimated parameters through a simulation to predict structural responses; and (iii) compared the structural response predictions to the predetermined nominal responses for structural integrity assessment. In this context, *system parameters* comprise both material properties and operational conditions. For example, the former includes Young's modulus and Poisson's ratio in the case of isotropic materials, and the latter contains force boundary conditions exerting on a structural system. *Response predictions* denote the predicted behavior of a structural system, such as natural frequencies and displacements. The *nominal* value refers to a quantity associated with the normal state of a system. For instance, the nominal material properties and operational conditions are the intact material properties and the hypothetical operational conditions, respectively. Similarly, the nominal response prediction is the response evaluated at the normal system parameters.

To realize the assessment strategy, we capitalized on (i) certified reduced basis (CRB) methods [20,21] to rapidly predict structural responses, and (ii) Bayesian statistical inference [22–28] to estimate system parameters under uncertainties. First, the CRB methods are useful because they expeditiously address parameterized partial differential equations (PDEs) on a reduced vector space for many-query and real-time applications. Unlike other model

E-mail address: aeronova@pusan.ac.kr

https://doi.org/10.1016/j.compstruc.2017.10.012
0045-7949/

approximation techniques, CRB methods equip with *a posteriori* error analysis to evaluate the approximation error bound of a reduced model without invoking the original full model. This error bound information is conducive to quantifying uncertainty resulting from model approximation in the context of inverse estimation. Next, Bayesian statistical inference is pragmatic because it estimates system parameters as a posterior probability distribution in consideration of uncertainties modeled by probability distributions. In addition, the Bayesian inference formulation comes with inherent regularization in the form of a prior probability distribution, which eases the ill-posedness of inverse estimation. In particular, a prior probability distribution is amenable to infuse objective information or subjective belief on parameters into the estimation process [29]. Since a structural system is typically nonlinear in system parameters, we drew on Markov chain Monte Carlo (MCMC) methods [30] to yield a posterior probability distribution while allowing for uncertainties stemming from measurement noise and CRB model approximation.

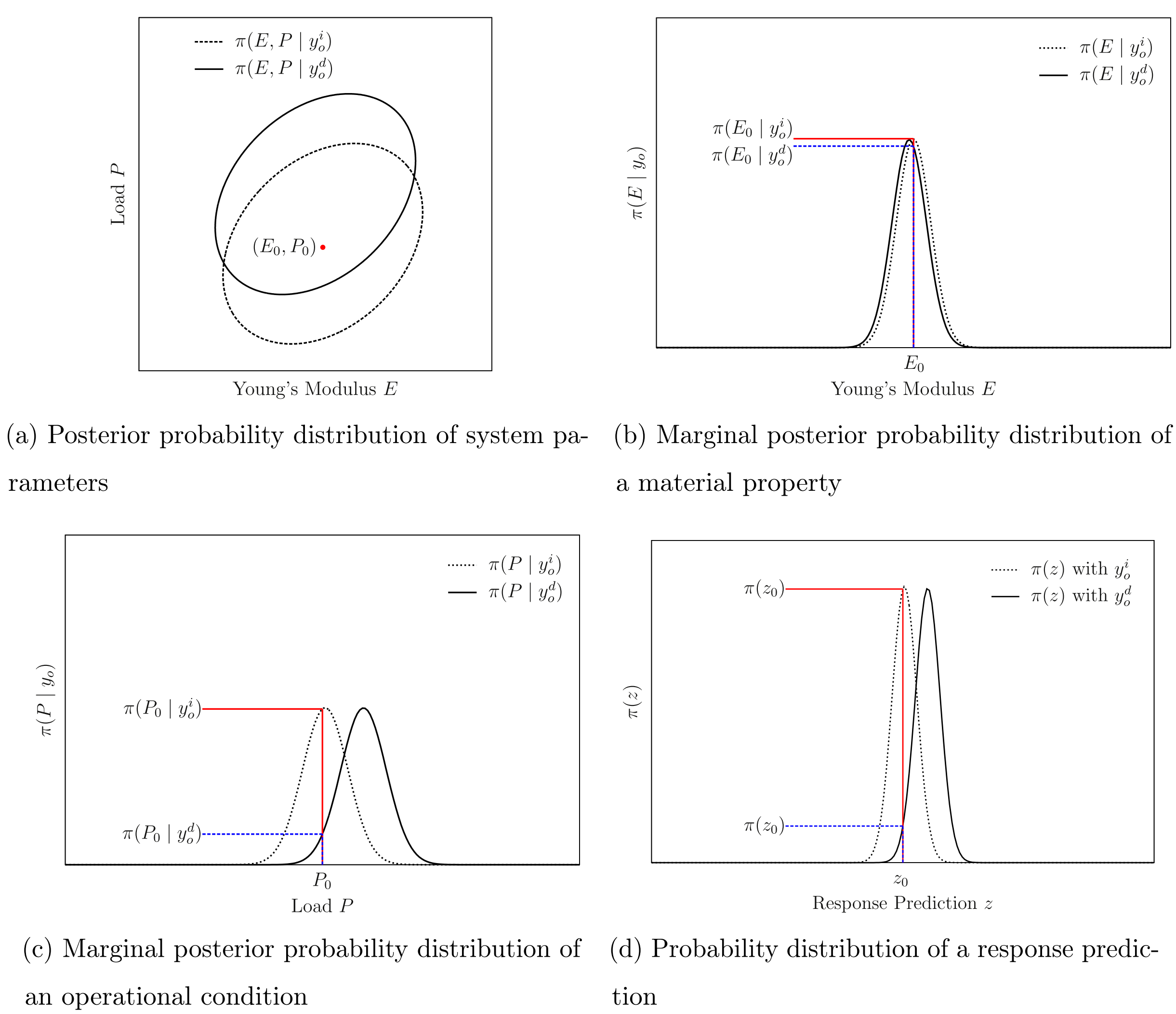
Overall, we proposed to delve into structural response predictions instead of material property estimates to reliably examine structural integrity under operational uncertainties. According to the Rytter's damage identification levels [8,31], the proposed strategy is capable of achieving the level 1, damage detection, and a part of the level 3, damage extent assessment. As for the outline, this paper is organized as follows. After the introduction, Section 2 presents the formulations of Bayesian inverse parameter estimation and structural response prediction. Section 3 delineates the construction of CRB models based on the linear elasticity theory. Section 4 illustrates the results of numerical investigation with beam and plate models, comparing the utility of structural response predictions to that of material property estimates. Section 5 summarizes the findings of this research.

2. Formulations

In this section, we briefly explain the proposed structural integrity assessment and the Bayesian statistical approach for inverse parameter estimation. To derive a posterior parameter distribution, we adopted a Gaussian prior distribution and a measurement likelihood constructed with a Gaussian measurement noise and uniform CRB model error. Afterwards, we describe the evaluation of structural response prediction, followed by an outline of the overall assessment procedure to examine structural integrity.

2.1. Structural integrity assessment

The proposed assessment strategy is based on the following conjecture: even though we may not correctly estimate system parameters due to operational uncertainties, we may still predict structural responses accurate enough to discern the presence of



(a) Posterior probability distribution of system parameters

(b) Marginal posterior probability distribution of a material property

(c) Marginal posterior probability distribution of an operational condition

(d) Probability distribution of a response prediction

Fig. 1. Conceptual illustration of the proposed structural integrity assessment with the 99.7% contours of Gaussian distributions.