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Matching experimental and three dimensional numerical models for structural vibration problems with uncertainties

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ABSTRACT

The simulation model which examines the dynamic behavior of real structures needs to address the impact of uncertainty in both geometry and material parameters. This article investigates three-dimensional finite element models for structural dynamics problems with respect to both model and parameter uncertainties. The parameter uncertainties are determined via laboratory measurements on several beam-like samples. The parameters are then considered as random variables to the finite element model for exploring the uncertainty effects on the quality of the model outputs, i.e. natural frequencies. The accuracy of the output predictions from the model is compared with the experimental results. To this end, the non-contact experimental modal analysis is conducted to identify the natural frequency of the samples. The results show a good agreement compared with experimental data. Furthermore, it is demonstrated that geometrical uncertainties have more influence on the natural frequencies compared to material parameters and material uncertainties are about two times higher than geometrical uncertainties. This gives valuable insights for improving the finite element model due to various parameter ranges required in a modeling process involving uncertainty.

1. Introduction

Accurate modeling and measurement of input parameters is the key to achieving reliable results which determine the dynamic behavior of real structures. Thus, it is essential to clarify the uncertainties involved both in the modeling and measurement process. Uncertainty quantification (UQ) is described as the study of discrepancy between simulation and experimental results [1]. This involves identifying all sources of uncertainty and the solution's sensitivity to these sources. Since the variability of uncertainties for complex structures can be quite pronounced, their quantification involves costly computational efforts making it even unfeasible in most cases. Therefore, defining a simplified model that represents the desired properties of the real structure is crucial. In this regard, simple beam element models are commonly used in finite element method (FEM) studies to quantify the effect of parameter uncertainties, cf. [2–4].

Uncertainties in finite element analysis can be described by many approaches, here we use an interval method (IM) approach. The fundamental aspect to these methods can be found in the literature, cf. [5,6]. General recommendations regarding model

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uncertainties that are important for modeling and for the development process are given in Ref. [7]. These recommendations include valuable ideas: important steps in the model validation process and how to represent results together with their uncertainties. Moore [6] reviewed several interval methods, which can be used to calculate solution limits corresponding to an interval of possible values for experimental results. Sim et al. [8] introduced an efficient modal interval analysis procedure where they identified bounded ranges of parameters and were able to validate the results by comparing them to Monte Carlo simulations. In general, interval arithmetic is a useful tool for describing the propagation of uncertainties for problems when it is not possible to obtain probabilities of different values, Broadwater et al. [9]. Kompella and Bernhard [10] introduced an approach to determine the uncertainty in a production line. Their findings emphasize the importance of uncertainties during production of the final product. They measured the statistical variation of a structural acoustic parameter of vehicles and compared it to a reference measurement value. This method has been applied in various practical engineering problems involving uncertainty and is well-explained in the literature, cf. [11–15]. In acoustics, Hills et al. [16] compared the measurement variability of audio–frequency response of a hatchback model with both a three–door (411 vehicles) and five-door (403 vehicles) derivative and a mid–sized family five-door car (316 vehicles). In summary, the frequency response function (FRF) varied by approximately $5-15$ dB over the frequency range between $0-1000$ Hz for the structure–borne and air–borne paths.

This paper discusses the accuracy of finite element solutions in terms of uncertainties in the model. These uncertainties are divided into two categories: those related to the properties of input parameters (e.g. Young's modulus, density, Poisson's ratio, and dimensions) and those related to the modeling process (approximation due to e.g. discretization or choice of boundary conditions). For characterization, the interval method is employed, see Section 2. The uncertainty of parameters related to material properties is obtained by performing measurements on beam-like steel structures with a parameter identification method described in Section 3.2. The presented ultrasonic measurement of the Young's Modulus E and the error calculation is more accurate than other common methods. Determining the material parameters using inverse modal analysis employing non-destructive identification technique possesses similar accuracy as shown in Refs. [17,18]. To this end, the quantified uncertainties are used as input parameters for the numerical models. These can be divided into one–dimensional or three–dimensional models. In the one–dimensional case, analytical solutions utilizing the Euler–Bernoulli or the Timoshenko beam theory are considered. In the three–dimensional case, a finite element model of the beam-like steel structure is used, utilizing structured hexahedral (brick) elements. Note that beam elements are not considered here because:

(i) their implementation is often based on one of the beam theories which is already covered by taking a one–dimensional model into account and
(ii) they are recommended not to be used in general real world applications, e.g. modeling an engine-transmission unit or a vehicle power train.

By dividing the model uncertainties into different categories and applying the interval method to each of them, the effect of specific uncertainties is presented.

This paper is structured as follows: In Section 2, the theory of interval method and modal analysis are briefly explained. The performed experimental modal analysis is presented in Section 3, whereas the parameter uncertainties and the results from numerical analysis are presented in Section 4. In Section 5, experimental and numerical results are compared. Finally, conclusions are drawn in Section 6. To the best of the authors knowledge this is an original documentation from the application of measured uncertainties, utilization of a finite element model towards a final uncertainty estimation of natural frequencies for a structure. The methods employed here can be easily transformed to real structures such as automobile engine-transmission units.

The following section is important since it shows that in finite element modeling, if the mass and stiffness matrix *uncertainties* are small, the expected uncertainty range for a natural frequency under these deviations due to uncertainty will also be small. In other words the range of uncertainty of one natural frequency is not expected to overlap with the expected range of it's neighbor.

2. Interval stochastic method and modal analysis

Modeling structural beam vibrations is traditionally performed using the lumped model in a single degree–of–freedom (SDOF) or multi degree–of–freedom (MDOF) system. The continuum-based theories employ the Euler-Bernoulli and Timoshenko beam theory in the form of partial differential equations. Detailed descriptions of these theories can be found in the literature [19,20]. Additionally, the finite element method can be employed to analyze the structural beam vibrations employing different finite elements, cf. [21–26] for instance. Regarding uncertainties, the stochastic finite element modeling uses various probabilistic and possibilistic methods. Among them, the interval stochastic method is chosen for the analysis of the beam-like structure because of its straightforward application. The applied interval operations and the performed interval-based stochastic modal analysis is briefly presented in the following. For an in–depth introduction to interval methods refer to Qiu et al. [27].

Assuming real numbers $\mathbb{R}$, a closed interval X^{I} is defined by

$$X^{\mathrm{I}} = [x_{\min}, x_{\max}] = \left\{ x \in \mathbb{R} | x_{\min} \leq x \leq x_{\max} \right\}, \qquad x_{\min}, x_{\max} \in \mathbb{R}, \tag{1}$$