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Application of a Bayesian algorithm for the Statistical Energy model updating of a railway coach

Mehran Sadri [a,b,*], Jonas Brunskog [a], Davood Younesian [b]

[a] Acoustic Technology, Department of Electrical Engineering, Technical University of Denmark, Ørsteds Plads 352, 2800 Kongens Lyngby, Denmark
[b] Center of Excellence in Railway Transportation, School of Railway Engineering, Iran University of Science and Technology, Tehran 16846-13114, Iran

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ABSTRACT

The classical statistical energy analysis (SEA) theory is a common approach for vibroacoustic analysis of coupled complex structures, being efficient to predict high-frequency noise and vibration of engineering systems. There are however some limitations in applying the conventional SEA. The presence of possible strong coupling between subsystems and the lack of diffuseness result in a significant uncertainty. This is the main motivation for the present study, where a procedure to update SEA models is proposed. The proposed procedure is the combination of the classical SEA method and a Bayesian technique. Due to reasons such as finding a limited number of important parameters, using a limited search range, avoiding matrix inversion and taking the effect of noise into account, the proposed strategy can be considered as a proper alternative to the experimental SEA approach. To investigate the performance of the proposed strategy, the SEA model updating of a railway passenger coach is carried out. First, a sensitivity analysis is carried out to select the most sensitive parameters of the SEA model. For the selected parameters of the model, prior probability density functions are then taken into account based on published data on comparison between experimental and theoretical results, so that the variance of the theory is estimated. The Monte Carlo Metropolis Hastings algorithm is employed to estimate the modified values of the parameters. It is shown that the algorithm can be efficiently used to update the SEA models with a high number of unknown parameters.

1. Introduction

Statistical energy analysis (SEA) [1,2], as developed in the 1960s by Lyon [3,4] and others, is an efficient method for obtaining response of complicated structures. It can be used to predict the band average ensemble of uncertain coupled systems. Many researchers have investigated the sound transmission in rooms and buildings [5–9], partitions and enclosures [10,11] and interior noise level of vehicles [12–16] by using SEA. In most of the studies, SEA parameters have been estimated by employing theoretical approaches. However, due to the uncertainties of the estimated parameters, a significant difference can be found between the predicted and measured results in many of these references. The presence of a strong coupling between SEA subsystems and the lack of diffuseness are important reasons for the uncertainty of such SEA models [17,18]. It is important to take the uncertainties of the classical SEA approach into consideration and to improve accuracy and reliability of classical SEA models by providing an appropriate updating strategy. The main goal of the present study is therefore to propose a strategy to update uncertain parameters of SEA models developed based on the classical SEA assumptions.

Different updating methods and frameworks have been proposed in previous studies to deal with the uncertainty of vibroacoustic systems. Some authors have used analytical and numerical procedures to analyze the acoustical performance of plate–cavity systems. By comparing the simulation and experimental results, they have employed different algorithms to update the uncertain parameters. Dhandole and Modak [19] employed the inverse eigen sensitivity method (IESM) to update the uncertain parameters of a vibro-acoustic finite element model. They considered uncertainty in the values of physical parameters and updated the frequency response of the vibro-acoustic model. They found that the employed method is computationally efficient. However, the IESM method is difficult to be utilized for complex models. Moreover, the proposed values for the updated parameters cannot be justified in a physical sense. A constrained model updating of an acoustic cavity has been carried out by Dhandole and Modak [20].

* Corresponding author at: Acoustic Technology, Department of Electrical Engineering, Technical University of Denmark, Ørsteds Plads 352, 2800 Kongens Lyngby, Denmark.

E-mail address: mehrsad@elektro.dtu.dk (M. Sadri).

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Lower and upper bounds have been taken into consideration in their study to obtain the physically meaningful values for uncertain parameters. However, it has been found that the convergence of the algorithm is significantly dependent on the chosen values for lower and upper bounds of parameters. Some sensitivity-based updating procedures have been utilized by different researchers to update the sensitive parameters of cavity models [21,22]. Generally, for sensitivity-based algorithms, the number of measurements must be larger than the number of parameters. Consequently, there is a significant limitation for employing these methods for updating the vibroacoustic models with many uncertain parameters. The important drawbacks of the updating procedures mentioned above can be listed as:

1. It is not easy to use the procedures, suggested by the previous studies, to update models with the non-parametric modeling uncertainty. This is due to the fact that no straightforward strategy has been provided in these studies, to reasonably limit the search space of updating algorithms and consequently to efficiently find physically meaningful values for parameters. Therefore, the proposed updating methods are not appropriate for models with a large number of uncertain parameters.
2. A large number of experimental data is needed to update the models with a noticeable number of updating parameters.

Although no study has been conducted to update the uncertain parameters of SEA models, different efforts have been made to investigate the influence of the uncertainty of physical parameters on the average energy response predicted by SEA models. The parametric uncertainty of material and geometric characteristics of mechanical systems are the main motivation for most of such studies. Radcliffe and Huang [23] predicted the mean values of sound and vibration for a vehicle by utilizing SEA. Employing an analytical approach, they investigated the response sensitivity to variances of the physical parameters of the vehicle. The main objective of their study was to help designers to estimate the distribution of the SEA energy response associated with the Gaussian distribution of the physical parameters considered at the design stage. Validity of the analytical method was checked by comparing the results with those obtained by the Monte Carlo technique. Standard deviation in subsystems response due to an uncertain coupling length between two plates has been examined by Büssow and Petersson [24]. It was assumed that the physical parameter has a normal distribution with a small variance which is considered as flexibility in design. Büssow and Petersson used a Taylor expansion to obtain the sensitivity of the energy response to parameters. However, assuming small variations for uncertainties is the main obstacle for applying the sensitivity-based procedures. Sensitivity of the energies, stored in SEA subsystems, to damping and coupling loss factors has been examined by Culla et al. [25]. They assumed that the uncertainty of SEA parameters (coupling loss factor and input power) is due to the variability of the material and geometric properties of systems. The parametric uncertainty was therefore taken into consideration in their study. Xu et al. [26] obtained the uncertainty in response of the structural–acoustic systems by two different methods. Nominal values were taken into account for material properties in their study and the uncertainty of the response was investigated by considering lower and upper bounds for the chosen parameters. Although obtaining the uncertainty in energies of SEA subsystems and sensitivity of them to material and geometric properties are of interest, updating the SEA parameters obtained by the classical SEA theory is necessary for engineering applications. In most of previous studies, the parametric uncertainty of SEA models is considered. The parametric uncertainty is due to random/unknown variations in physical parameters such as stiffness modulus and geometry. The non-parametric and modeling uncertainties of SEA models should be taken into a serious consideration as well. The non-parametric uncertainty is due to variations within the ensemble fulfilling the same SEA system, thus having the same parameters but different realisations within these limits. The non-parametric uncertainty of SEA models has been investigated by Langley and Cotoni [27]. Modeling uncertainty is an important non-parametric uncertainty. Modeling uncertainty is due to modeling errors due to limitations in SEA and violation of the underlying assumptions. Investigation of the modeling uncertainty for hybrid FE-SEA models has been carried out by Cicirello and Langley [28,29]. The present study is mainly concerned with the modeling uncertainty. However, the parametric uncertainty is also indirectly taken into account by using the proposed procedure (explained below) in the present study. The second type of uncertainty (non-parametric) deals with the uncertainty due to the difference between the ensemble and a single realisation. This is not included in the present study. However, for complex systems with many modes within the considered frequency band, this noise/uncertainty is very limited.

The modeling uncertainty of SEA models must be investigated for cases which the essential assumptions of the conventional SEA are not fully satisfied for all parameters or no appropriate theoretical formula can be found to estimate the SEA parameters. To overcome such a problem, different researchers have employed the experimental SEA approach [30–34]. By using the experimental SEA method, a known input power is applied and the energy response of a structure is measured first and the unknown internal and coupling loss factors of the structure are then estimated by using a matrix inversion. There are however several difficulties in applying the experimental SEA approach for the estimation of the SEA parameters. The number of unknown coupling loss factors for complex structures is very large and it is larger than the measured data points. Many measured results must therefore be provided. Otherwise, the approach results in an under-determined problem. Therefore, the problem is typically ill-posed. Moreover, there are several numerical difficulties due to the matrix inversion in presence of noise.

Based on the findings of previous studies, it can be concluded that a new procedure should be provided to avoid the possible problems of current updating strategies. The present study is therefore intended to propose an updating procedure, which can be employed to improve the accuracy of SEA models. A Bayesian framework is consequently proposed for this purpose. To investigate the performance of the proposed approach, a passenger coach is taken into consideration and the uncertain parameters of the system are updated. Due to the presence of some stiff components in the vehicle structure under study, a Hybrid FE-SEA [35] model was developed first. The stiff longitudinal and transverse beams were considered as FE subsystems and the other components were modeled as statistical subsystems. An acoustic excitation has been applied in this study and sound pressure response of the interior cavities is obtained. However, due to the fact that the FE part of the model is analyzed as a deterministic part and based on the similar results obtained from the Hybrid FE-SEA and SEA analysis of the acoustically excited system, a pure SEA model is chosen in this study.

The proposed strategy in this paper is based on a combination of the classical SEA method and a Bayesian technique. The proposed approach can be considered as a sound alternative to the experimental SEA method. The experimental SEA method is not applicable for determining unknown SEA parameters of models with a large number of subsystems. Moreover, the experimental SEA approach is significantly sensitive to noise. The problems of the experimental SEA can be avoided by using the proposed strategy. The reasons for this are summarized in the following points: