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Global sensitivity analysis and uncertainties in SEA models of vibroacoustic systems

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ABSTRACT

The effect of parametric uncertainties on the dispersion of Statistical Energy Analysis (SEA) models of structural-acoustic coupled systems is studied with the Fourier analysis sensitivity test (FAST) method. The method is firstly applied to an academic example representing a transmission suite, then to a more complex industrial structure from the space industry. Two sets of parameters are considered, namely error on the SEA model's coefficients, or directly the engineering parameters. The first case is an intrusive approach, but enables to identify the dominant phenomena taking place in a given configuration. The second is non-intrusive and appeals more to engineering considerations, by studying the effect of input parameters such as geometry or material characteristics on the SEA outputs. A study of the distribution of results in each frequency band with the same sampling shows some interesting features, such as bimodal repartitions in some ranges.

1. Introduction

Vibroacoustic design is a topic of great importance in many engineering sectors. Especially in the transportation industries, both on the ground or in aeronautics, noise and vibration have to be addressed in order to achieve competitive products. This has even become more important since a trend towards lightweight design has initiated in order to improve energy efficiency, which has the downside of degrading noise and vibration performance. The wide frequency spectrum which has to be studied leads to different methodologies in handling vibroacoustic problems: some methods deal primarily with low frequencies, and others with high frequencies. Statistical Energy Analysis (SEA) [1] belongs to the second category. It is a widely-used method, which considers average energy quantities through energy balance. SEA modelling is quite simple. The system is divided into simple substructures, and the power balance leads to an algebraic equations giving the total energy stored within each of them. This model requires knowledge of several coefficients, which can be difficult to estimate reliably. For instance, the energy flow balance needs the damping loss factor (DLF) to be provided for each subsystem. The coupling loss factor (CLF) of each couple of subsystems is also needed to close the analytical formulation. CLF and DLF are often provided by a database of materials and interfaces. These quantities can also be estimated experimentally or numerically. The literature about SEA reports a significant amount of publications dealing with SEA inputs estimation in vibroa-

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coustic contexts, either analytically [1] or deriving from finite element models [2,3]. The impact of the variability of such inputs on the SEA design can be of great interest at the pre-design stage.

Uncertainty and variability are the core of the SEA approach, as it deals with ensemble statistics rather than deterministic quantities. However, the actual averaging lies in the SEA hypotheses rather than in the mathematical formulation itself, and the account of uncertainty is not explicit in classical SEA. Fahy and Mohammed [4] investigated the effect of uncertainties on the output variance of power flows in SEA systems composed of coupled plates and beams. Work has been done by Langley and Brown [5,6] to estimate the variance of the kinetic energy of an SEA subsystem. This was extended and validated in [7] for systems with only structural components. Uncertainties in SEA models have been studied by several authors as well: Culla et al. [8] used partial derivative analysis and Design of Experiment (DoE) techniques to study the sensitivity of models to the SEA factors. Partial derivative sensitivity was also used for transfer path analysis by Büssow and Petersson [9]. The effect of the variance of SEA coupling loss factors on transfer path analysis is studied by Aragonés and Guasch [10]. Cicirello and Langley [11] also studied the sensitivity of a mixed FE-SEA model to both parametric and non-parametric uncertainties. Xu et al. [12] proposed two methods to estimate the interval of variability of SEA results for structural-acoustics coupled systems.

The objective of this work is to contribute to the quantification of uncertainty due to model inaccuracy, by establishing a ranking of the most influential parameters of a SEA model. Global sensitivity analysis in general is used to derive indicators of influence for parameters which have broad variation ranges, as opposed to local methods which target variations around a working point. There are several ways of deriving global indicators [13]. Among these, the class of methods grouped under the term ANOVA (acronym of Analysis of Variance) are based on the variance decomposition [14] as an estimate for the sensitivity of each parameter. The Fourier amplitude sensitivity test (FAST) is one of these methods, which was originally developed by Cukier et al. [15] as a computationally efficient method to compute the ANOVA sensitivity indices, with application in the study of complex chemical reactions. This method has later been reused by Iooss et al. [16] for radiologic risk assessment models. Ouisse et al. [17] applied the FAST method to porous material models, regarding acoustic impedance and absorption. This work was later extended to different models of porous materials with focus on microgeometry in [18]. The parametric approach proposed here can be used both for lack of knowledge of parameters, or for model inaccuracies, and so be used in combination with an interval analysis such as the one proposed by Reynders [19].

SEA models are subject to uncertainty in two forms: lack of knowledge of the input parameters, and modelling errors in evaluating the damping and coupling coefficients. The originality of the present work lies in the application of an ANOVA global sensitivity analysis method to an SEA model in order to identify the contribution of every uncertain parameter to the output variance. Both modelling uncertainties and input parameter variability can be handled in the proposed framework.

The method is first presented on the academic case of noise transmission between two reverberant rooms through a composite plate. Variation on the coupling coefficients enable to highlight the dominant phenomena occurring in the model. The effect of engineering parameters is then studied on the same academic set-up and an industrial structure. Because the FAST method is a sampling method, the values at samples can also be recovered and used in a statistical analysis enabling to get more information about the distribution, such as the standard deviation or simplified models of the probability law.

This paper is structured as follows: Section 2 presents the general SEA model that will be used for the academic case. A brief overview of the FAST sensitivity analysis method is presented in Section 3. The uncertainty of modelling itself is investigated on the academic transmission suite case in Section 4. Finally, the effect of uncertainties on engineering parameters is studied in Section 5 with the same transmission suite example and an industrial test case.

2. SEA modelling

2.1. General SEA equations

SEA modelling is based on the analogy between energy exchanges in vibrating systems and heat transfer between bodies at different temperatures. The mechanical system is decomposed into N elementary subsystems. The power flow between each pair of subsystems is supposed to be proportional to the difference between their total vibrational energies. In addition, each system can dissipate energy, again proportionally to its energy level. The power transferred from subsystem i with total energy E_i to subsystem j with energy E_j in the band centred around frequency f is written

$$P_{ij} = \omega\left(\eta_{ij}E_i - \eta_{ji}E_j\right), \tag{1}$$

where $\omega = 2\pi f$, η_{ij} and η_{ij} are called coupling loss factors (CLF), while the power dissipated in system i is

$$P_{i,diss} = \omega\eta_i E_i, \tag{2}$$

where η_i is the damping loss factor (DLF). All these coefficients depend on the nature of the subsystems and their coupling, as well as on the width of the frequency band considered. The CLFs obey a reciprocity rule, as $\eta_{ij}n_i = \eta_{ji}n_j$ where n_i and n_j are the modal densities of systems i and j. The SEA system is obtained by writing the power balance of each subsystem, where the injected power equates the power losses due to dissipation and couplings: