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Abstract: This paper gives a concise but comprehensive brief survey of an approach for predicting the frequency response functions of general complex structural-acoustics systems in the low- and medium-frequency ranges. Modeling is based on the use of fuzzy structure theory, introduced by the author in 1985, including recent developments concerning identification of the fuzzy substructure model parameters. This theory allows the effects of the internal structural complexity on the master structure to be modeled. For solving the equation with random operator in the MF range, we propose the use of an intrinsic reduced model of the frequency response functions, recently proposed by the author, which allows the calculation of the responses to any deterministic or random excitations.

FUZZY STRUCTURE THEORY FOR MODELING STRUCTURAL COMPLEXITY

The objective of the fuzzy structure theory introduced by the author in 1986 (1), extended in 1993 (2) and 1996 (3), re-explained and summarized in 1998 (4), is to predict the MF local dynamical response of a master structure coupled with a large number of complex secondary subsystems such as equipment units or secondary structures attached to the master structure. These subsystems are called fuzzy substructures due to their structural complexity and because the details on them are unknown, or are not accurately known. This explains the choice of the word "fuzzy" proposed in (1). The terminology "fuzzy" has nothing to do with the mathematical theory concerning fuzzy sets and fuzzy logic. This fuzzy structure is coupled with an external acoustic fluid via the master structure (and possibly, with internal acoustic fluids (4)). The objective of the fuzzy structure theory is to predict the modulus and phases of the master-structure displacement field and of the acoustic pressure field radiated by the master structure, taking into account the fuzzy substructures attached to the master structure, but not to predict the dynamical response of fuzzy substructures. Consequently, the fuzzy structure theory differs from Statistical Energy Analysis (5) which deals with the prediction of the energy of each mechanical primary and secondary subsystem. Since 1991, much research has been published by the American scientific community in this area. We can mention (6) to (15) for the particular problem of a master structure coupled with a large number of simple linear oscillators, (16) for a complex experiment concerning the effect of internal oscillators on the acoustic response of a submerged shell, (17) for design criteria concerning the damping effectiveness of fuzzy structures, (18) for investigating the fuzzy structure behaviors in terms of impulse response function. We present hereinafter a brief survey on the fuzzy structure theory developped by the author.

Concept of fuzzy structure. A fuzzy structure is defined as a master structure that is accessible to conventional modeling, coupled with fuzzy substructures which are not accessible to conventional modeling

due to the structural complexity of secondary subsystems and because details on them are unknown, or are not accurately known.

Effects of fuzzy substructures on the dynamical response of the master structure. Since each fuzzy substructure is constituted by a large number of discrete or continuous weakly damped bounded structures, a fuzzy substructure is a resonant mechanical system with a high modal density in the frequency band of interest. Experimental results show that the presence of fuzzy substructures induces an "apparent strong damping" in the master structure in the MF range (1) and possibly in the LF range (19). The resonance morphology is strongly attenuated for the master structure. This phenomenon can be explained by the net transmitted power flowing from the master structure to the fuzzy substructures.

Fuzzy structure theory stated as an inverse problem. Let $\mathbf{Z}_\Sigma(\omega)$ be the boundary impedance operator related to interface Σ between the master structure and a fuzzy substructure, modeling the effects of the fuzzy substructure on the master structure (concerning the existence of such a boundary operator, we refer the reader to (4)). In a context of a classical structural-dynamics problem with random uncertainties, this operator depends on a vector-valued uncertain parameter $\mathbf{y}$ and the mapping $\mathbf{y} \mapsto \mathbf{Z}_\Sigma(\omega\,;\mathbf{y})$ is assumed to be known. Consequently, the random boundary impedance operator is the operator-valued random variable $\mathbf{Z}_\Sigma(\omega\,;\mathbf{Y})$ in which $\mathbf{Y}$ is the vector-valued random variable modeling uncertain parameter $\mathbf{y}$. In the context of the fuzzy structure theory introduced by the author (1), mapping $\mathbf{y} \mapsto \mathbf{Z}_\Sigma(\omega\,;\mathbf{y})$ is unknown by definition, i.e. cannot be constructed due to the complexity of the mechanical subsystem, which is partially unknown from a geometrical and mechanical point of view. Consequently, the direct approach cannot be applied. The fuzzy structure theory is then constructed as an inverse problem and is not a classical structural-dynamics problem with random uncertainties. Since a fuzzy substructure consists of a large number of secondary subsystems inaccessible to conventional modeling, a statistical approach is used for directly constructing a random boundary impedance operator $\mathbf{Z}_{fuz}(\omega)$ (playing the role of unconstructible random variable $\mathbf{Z}_\Sigma(\omega\,;\mathbf{Y})$) related to interface Σ and representing the effects of the fuzzy substructure on the master structure.

Random equation of the external structural-acoustics system with fuzzy substructures. This equation is written as

$$i\omega\left(\mathbf{Z}_{mast}(\omega) + \mathbf{Z}_{fuz}(\omega) + \mathbf{Z}_{acous}(\omega)\right)\mathbf{U}(\omega) = \mathbf{f}(\omega) \quad, \tag{1}$$

in which $\mathbf{Z}_{mast}(\omega)$ is the impedance operator of the master structure, $\mathbf{Z}_{fuz}(\omega)$ is the random boundary impedance operator representing the effects of the fuzzy substructures on the master structure, $\mathbf{Z}_{acous}(\omega)$ is the acoustic impedance boundary operator representing the effects of the external acoustic fluid on the master structure (2,4), $\mathbf{U}(\omega)$ is the random displacement field of the master structure and $\mathbf{f}(\omega)$ represents the external forces applied to the master structure.

Modeling the fuzzy substructures. As an inverse problem, random boundary impedance operator $\mathbf{Z}_{fuz}(\omega)$ is constructed using the concept of a type I or type II homogeneous fuzzy impedance law. For each fuzzy substructure, the fuzzy impedance law depends on a set of parameters called the mean coefficients (mean coefficients of the participating mass, mean rates of internal damping, mean modal densities and mean equivalent coupling factors) and the associated deviation coefficients of the law (see ref. (1),(2) and (4)).

Solving method for the random equation. Equation (1) with random operator is solved using a recursive method deduced from the use of a Neumann series expansion (see ref. (1) to (4), (20)).

Identification method for the parameters of type I and type II fuzzy impedance laws. The mean coefficients of the participating mass of the fuzzy substructures cannot easily be estimated and a systematic identification procedure must be used. Such an identification method has been proposed by the author (see ref. (3) and (4)) and leads to solving a constrained optimization problem related to the mean power flow equation for the master structure coupled with the fuzzy substructures.
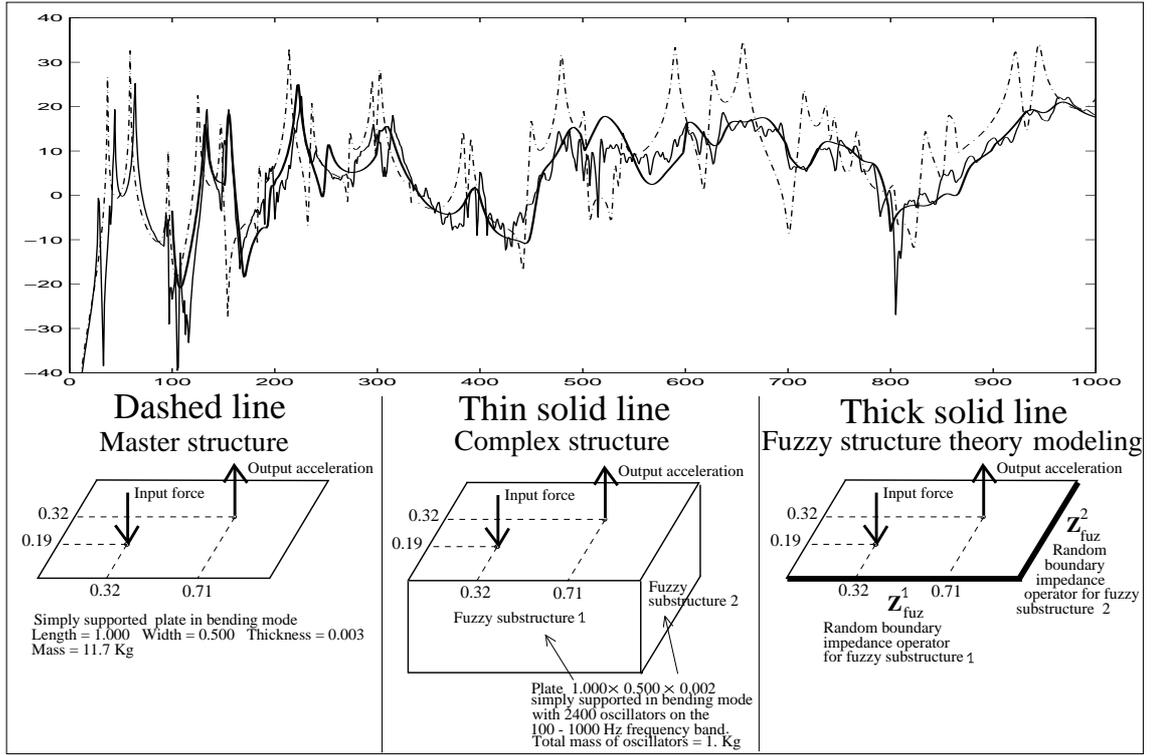
FIGURE 1. Fuzzy structure theory for a continuous-attachments case. Modulus (in dB) of the cross frequency response function between input force and output acceleration of the master structure in the 0 - 1000 Hz frequency band: (1) for the master structure with no fuzzy substructure (dotted line); (2) for the complex structure, i.e. the master structure coupled with 2 fuzzy substructures (thin solid line); (3) for the modeling of the complex structure using the fuzzy structure theory (thick solid line) and for which the cross frequency response function is associated with the inverse of operator $i\omega\left(\mathbf{Z}_{mast}(\omega) + E\{\mathbf{Z}_{fuz}(\omega)\}\right)$ in which E denotes the mathematical expectation.

Example of a master structure with two fuzzy substructures continuously attached to the master structure. The master structure is a plate in bending mode, continuously attached to two fuzzy substructures (see Figure 1). Each fuzzy substructure is constituted by a plate in bending mode with 2400 oscillators randomly distributed over the plate and in the 100 - 1000 Hz frequency band. Due to the continuous attachment, the type II fuzzy law is used with a mean equivalent coupling factor equal to 0.005. The mean coefficients of the participating mass were determined using the identification method evoked above.

REDUCED MODEL FOR STRUCTURAL-ACOUSTICS SYSTEMS WITH STRUCTURAL COMPLEXITY

Reduced model. The reduced model adapted to a frequency band B is obtained using the Ritz-Galerkin projection of Eq. (1) on an N-dimensional subspace V^N of the admissible displacement fields V of the master structure, spanned by an appropriate vector basis $\{\mathbf{e}_1, \ldots, \mathbf{e}_N\}$. For all $\omega \in B$, the approximation $\mathbf{U}^N(\omega)$ of solution $\mathbf{U}(\omega)$ of Eq. (1) is then written as $\mathbf{U}^N(\omega) = \sum_{j=1}^{N} Q_j(\omega)\,\mathbf{e}_j$ and $\mathbf{Q}(\omega) = (Q_1(\omega), \ldots, Q_N(\omega)\}$ is the solution of the random matrix equation on $\mathbb{C}^N$,

$$i\omega\left([\mathcal{Z}_{mast}(\omega)] + [\mathcal{Z}_{fuz}(\omega)] + [\mathcal{Z}_{acous}(\omega)]\right)\mathbf{Q}(\omega) = \mathbf{F}(\omega) \quad . \tag{2}$$

Since N is small, matrix Eq. (2) can be solved frequency-by-frequency.

Reduced model in the LF range. It is known (see ref. (21) to (24)) that, for low-frequency (LF) dynamic analysis in structural dynamics, reduced models are a very efficient tool for constructing the solution.

For instance, for the choice of basis $\{\mathbf{e}_1, \ldots, \mathbf{e}_N\}$, these techniques correspond to the use of the normal modes corresponding to the lowest eigenfrequencies of the associated conservative master structure and are called the modal reduction. The efficiency of this kind of reduced model is due to the small number N of generalized dynamical degrees of freedom $\mathbf{Q}(\omega)$ used in the representation and in addition, is obtained by solving a well-stated generalized symmetric eigenvalue problem for which only the first eigenvalues and the corresponding eigenfunctions have to be calculated (25). In addition, when such a reduced model (defined by Eq. (2)) is obtained, responses to deterministic and random excitations (see ref. (26) to (30)) can be calculated for no significant additional numerical cost, and the reduced model can be used directly for solving various structural-acoustic problems in the LF range (see ref. (31) to (33), (4), (19)).

Reduced model in the MF range. The fundamental problem related to the construction of a reduced model in the medium-frequency (MF) range for general dissipative structural-dynamics and structural-acoustics systems has not yet been solved. Methods based on the use of the normal modes in the MF and HF ranges have been proposed (see for instance (34)), but these methods can only be used for simply shaped structures in a context of an analytical theory.
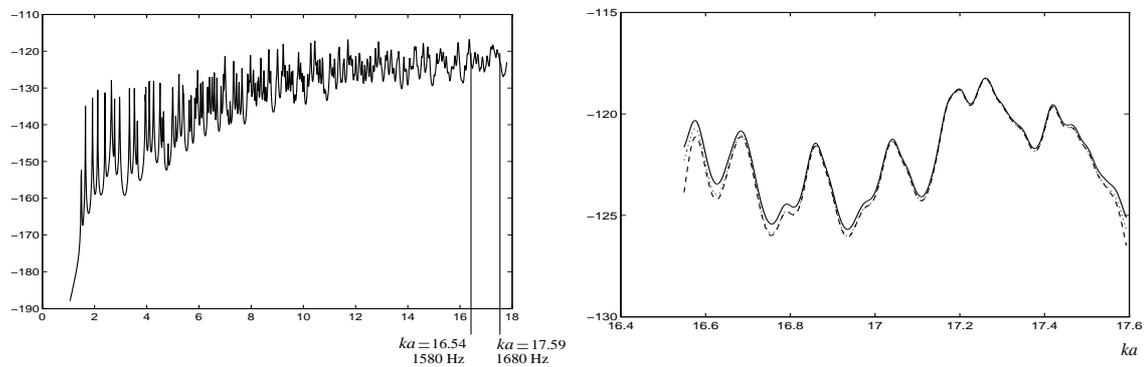

FIGURE 2. Spectrum in dB of the far field radiated in an oblique direction by a cylindrical elastic shell coupled with an external gas. The figure on the left shows the reference solution on a broad frequency band. The figure on the right shows the comparison on an MF narrow band between the reference solution (solid line) and the approximate solution obtained by the MF reduced model approach for different values of dimension N: $N = 25$ (dashed line), $N = 30$ (dotted line) and $N = 40$ (dashdot line)).

As a continuation of initial papers (35) concerning MF linear vibrations in structural dynamics, the author recently proposed a method in the MF range for constructing such a reduced model for general dissipative structural-dynamics (36, 4) and external structural-acoustics systems (37). To do so, for a fixed MF band B an energy operator related to the dynamics of the master structure in band B, is introduced. This operator is symmetric positive definite and has a countable set of positive eigenvalues. The corresponding eigenfunctions form a complete family in V. The reduced model adapted to MF band B is introduced using as subspace V^N of V, the dominant eigensubspace of the energy operator, spanned by the eigenfunctions $\{\mathbf{e}_1, \ldots, \mathbf{e}_N\}$ which correspond to the highest eigenvalues. Figure 2 shows a validation of this theory for a finite length circular cylindrical elastic shell coupled with several dashpots and springs and immersed in a gas. The two figures correspond to the normalized spectrum in dB (expressed as a function of the reduced wave number ka) of the far field radiated in an oblique direction by the structure coupled with a gas and excited by a time-stationary stochastic force field applied to the structure.

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