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Epistemic uncertainty propagation in energy flows between structural vibrating systems

Menghui Xu [a,b], Xiaoping Du [b], Zhiping Qiu [a,*], Chong Wang [a]

[a] Institute of Solid Mechanics, Beihang University, Beijing 100191, PR China
[b] Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65401, USA

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ABSTRACT

A dimension-wise method for predicting fuzzy energy flows between structural vibrating systems coupled by joints with epistemic uncertainties is established. Based on its Legendre polynomial approximation at $\alpha=0$, both the minimum and maximum point vectors of the energy flow of interest are calculated dimension by dimension within the space spanned by the interval parameters determined by fuzzy those at $\alpha=0$ and the resulted interval bounds are used to assemble the concerned fuzzy energy flows. Besides the proposed method, vertex method as well as two current methods is also applied. Comparisons among results by different methods are accomplished by two numerical examples and the accuracy of all methods is simultaneously verified by Monte Carlo simulation.

1. Introduction

It is noted that the study of the coupling of multimodal systems has been being an interesting topic for both low-medium frequency and high frequency problems over the past decades. And the energy-based methods, e.g. Statistical Energy Analysis (SEA) [1–5], are habitually used to predict the vibrational behavior of complex systems, where one of the fundamental researches is the investigation of the energy flows between mechanical subsystems. However, all real-life problems have been recognized to involve uncertainties to varying degrees due to physical imperfections, model inaccuracies and system complexities. These uncertainties, in general, significantly affect the system performance. The prior to the uncertain analysis of multimodal systems is the quantification of uncertainties, for which there have been three types of approaches [6], namely, theory of probability and random processes, convex set-theoretical analysis, and fuzzy sets based on the nature of uncertainties. From the published literatures, probabilistic methods are especially suitable in case of uncertainty due to randomness for which the information on both the range and probability density function are available [7].

Built-up structures are commonly assembled by connecting their components via bolts, rivets, and pins. The primary effect of these mechanical joints on the vibrational behavior of systems is due to their significant sources of damping. Furthermore, the net stiffness of the joint is affected not only by the elastic properties of its materials but also the hardness and roughness of the contact surfaces [8]. These properties are extremely difficult to model in detail and can vary substantially both during the life of a given joint and from one joint to another under nominally similar assembly process and environmental conditions [8]. And simultaneously it is noted that the variability is, in general, more pronounced for stiffness

* Corresponding author.
E-mail addresses: zpqiu@buaa.edu.cn (Z. Qiu).

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and damping parameters of a complex system than for its geometry [9]. Determining the uncertainties in mechanical joints is vital to model correctly the global system. Under the hypothesis of a small perturbation, the statistics of the energy flows and their scatters between the coupled two-subsystems have been calculated by probabilistic methods [10]. However, uncertain parameters such as damping and stiffness in mechanical joints are usually not measurable [11], which results in limited information available to obtain a good estimate of the statistics, and instead a group of experts has been polled to give their best estimate of the bounding values of these uncertain parameters. And thus epistemic uncertainties are introduced. For example, the stiffness and damping of bolted joints were represented by fuzzy-valued parameters quantified on the basis of measured data [12,13], and fuzzy arithmetic operations were applied to simulate and analyze the friction interface between the sliding surfaces of a bolted joint [14]. The treatment of joint uncertainties was also described in [15] by theories of fuzzy sets and demonstrated by different joints. And two methods for quantifying epistemic uncertainties in the modeling of joints were developed and subsequently applied to the bolted connection between the blade and the hub of the Ampair 600 Wind Turbine [16]. It is noted that the fuzzy quantification of uncertainties can be implemented by utilizing the alpha-cut technique, which converts a fuzzy analysis model into a set of nested interval evaluation problems at different alpha levels, and the possibility distributions of the system responses can subsequently be estimated.

In the context of interval analysis, the original one is the interval arithmetic approach, where all basic deterministic algebraic operations are replaced by their interval arithmetic counterparts. The interval of the energy flow between two structural multimodal systems has been determined using the interval arithmetic approach by Gabriele et al. [9] where the joint parameters are considered as interval variables. And for the same problem, the interval of the energy flow has also been calculated by Wu et al. [17] based on its surrogate models established by Taylor series expansion method. However, the interval arithmetic method has been proved to be of little practical use for realistic problems involving multiple occurrence of the same interval variable due to its conservative estimation for the system response. Accordingly approaches such as the interval/subinterval perturbation method [18,19] and equivalent transformation method [20] only for interval analysis, vertex method [21–23] and global optimization-based methods [6,24–28] for both interval and fuzzy analysis have been proposed for solutions of interval problems. Besides, notable works have also been reported in the area of fuzzy analysis and methods including fuzzy perturbation method [29], fuzzy arithmetic method [30–33], transformation method [14,34–36], and component mode transformation method [37] have been theoretically established and applied in fuzzy solutions of specific problems. Unfortunately, each of these techniques has its specific limitations in applications and none of them has been established as the standard interval or fuzzy analysis procedure. Until now, research on the propagation of the epistemic uncertainty as well as the non-probabilistic uncertainty is limited but promising.

The aims of the present study includes: (1) investigating epistemic uncertainty propagation which also applies to non-probabilistic uncertainty propagation in energy flows between mechanical subsystems; (2) proposing a novel interval analysis method (at any alpha level for fuzzy analysis problems) to overcome limitations of current uncertainty propagation analysis methods. The rest of this study is organized as follows: the statement of energy flow prediction is given in Section 2 and two methods for this problem are subsequently reviewed. The procedure for the proposed method for epistemic uncertainty propagation is developed in Section 3 followed by two numerical examples in Section 4 for its verification. And the final conclusions are drawn in Section 5.

2. Preliminary

2.1. Problem statement

For comparisons between different methods, the problem investigated herein is the same as that discussed in Refs. [9,17], i.e. two multi-degree-of-freedom (multi-dof) subsystems coupled by a massless non-conservative joint (Fig. 1). Subsystem I is excited by a harmonic force $f_1 = F_1 e^{j\omega t}$ at point 1 and coupled with subsystem II by a linear massless joint III at points 2 and 3.

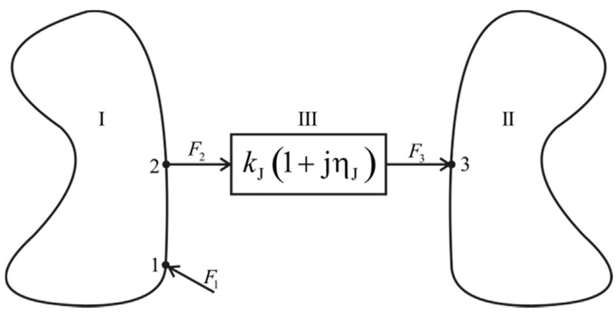

Fig. 1. Two multi-dof subsystems coupled by a massless joint.