Mechanical Systems and Signal Processing 93 (2017) 351–367

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Effect of model-form definition on uncertainty quantification in coupled models of mid-frequency range simulations

Kendra L. Van Buren [a,b], Morvan Ouisse [a,*], Scott Cogan [a], Emeline Sadoulet-Reboul [a], Laurent Maxit [c]

[a] Univ. Bourgogne Franche-Comté – FEMTO-ST Institute, CNRS/UFC/ENSMM/UTBM, Department of Applied Mechanics, 24 rue de l'épitaphe, 25000 Besançon, France
[b] Engineering Institute, Los Alamos National Laboratory, Los Alamos, NM, USA
[c] Univ Lyon, INSA Lyon, LVA EA677, 69621 Villeurbanne, France

ARTICLE INFO

Article history:
Received 29 May 2015
Received in revised form 7 February 2017
Accepted 11 February 2017

Keywords:
Uncertainty quantification
Statistical energy analysis
Statistical modal energy distribution analysis
Model reduction

ABSTRACT

In the development of numerical models, uncertainty quantification (UQ) can inform appropriate allocation of computational resources, often resulting in efficient analysis for activities such as model calibration and robust design. UQ can be especially beneficial for numerical models with significant computational expense, such as coupled models, which require several subsystem models to attain the performance of a more complex, inter-connected system. In the coupled model paradigm, UQ can be applied at either the subsystem model level or the coupled model level. When applied at the subsystem level, UQ is applied directly to the physical input parameters, which can be computationally expensive. In contrast, UQ at the coupled level may not be representative of the physical input parameters, but comes at the benefit of being computationally efficient to implement. To be physically meaningful, analysis at the coupled level requires information about how uncertainty is propagated through from the subsystem level. Herein, the proposed strategy is based on simulations performed at the subsystem level to inform a covariance matrix for UQ performed at the coupled level. The approach is applied to a four-subsystem model of mid-frequency vibrations simulated using the Statistical Modal Energy Distribution Analysis, a variant of the Statistical Energy Analysis. The proposed approach is computationally efficient to implement, while simultaneously capturing information from the subsystem level to ensure the analysis is physically meaningful.

1. Introduction

In design and analysis, numerical models have traditionally been pursued to gain insight into the performance of structures that are costly to build, potentially shortening the design-build-test cycle. With modern-day computing resources, it is now possible to develop more complex numerical models that are capable of incorporating a higher fidelity representation of physics processes at resolutions that were previously impossible to achieve. In particular, it has become common to pursue coupled models, whereby several numerical models are utilized to represent the overall behavior of a more complex, inter-connected system. Herein, coupled models are those models whose physics processes are simulated utilizing two or more numerical models, of either the same or differing physics. The output of the individual numerical models are then integrated

* Corresponding author.
E-mail address: morvan.ouisse@femto-st.fr (M. Ouisse).

http://dx.doi.org/10.1016/j.ymssp.2017.02.020

to obtain the desired quantities of interest. Such examples can include sub-structuring analysis of a finite element (FE) simulation, or pursuing fluid-structure interaction with computational fluid dynamics and FE simulations. It is emphasized, however, that there are unavoidable sources of assumptions and uncertainty in the development of these numerical models that must be accounted for so that they can be used reliably for decision-making purposes. In the development of these numerical models, assumptions enable model development but simultaneously limit the ability of the model to replicate reality.

The desire to utilize numerical models in a predictive capacity has given rise to uncertainty quantification (UQ), which is a field of research that focuses on understanding how predictions of a numerical model are affected by sources of uncertainty and assumptions inherent to the model. Such activities that contribute toward uncertainty quantification include parametric studies, effect screening, sensitivity analysis, and the forward propagation of uncertainty, the goals of which contribute to efficient numerical optimization and robust design. Thus far, UQ has gained much maturity for models that require only one forward calculation. UQ of coupled numerical models has received some attention in the published literature, however, it will undoubtedly continue to receive scientific interest due to the increased sources of assumptions that are necessary in order to couple several models together.

The basic flowchart of the coupled model paradigm addressed in this manuscript is outlined in Fig. 1. This coupled model paradigm is commonly referred to as a *weakly coupled* model, where subsystem models are used to generate inputs for coupled models. This is unlike *strongly coupled* models where there can be feedback between models at the subsystem and coupled model levels. There are two levels of analysis that are identified in the figure. The first level of analysis is where N subsystem models, $y_{s,i} = f_{s,i}(\theta_{s,i}; p_{s,i})$, $i = 1, \ldots, N$, are defined. Uncertain calibration parameters, $\theta_{s,i}$, are those that are introduced by environmental conditions and modeling choices whereas control parameters, $p_{s,i}$, are dimensions of the parameter space controlled by the analyst. The subsystem models serve an integral purpose in order to calculate the final quantities of interest, for example, use of a computational fluid dynamics code that might be used to determine forces that are applied to a finite element model, or a micro-scale model of material behavior used to characterize the stress-strain characteristics of a macro-scale material model. The subsystem level is thus the first level way of considering a system to compute primary responses of the system that will serve the second level named the coupled level.

Generated from the subsystem models are outputs, y, which are then used to define the inputs for the M coupled model solvers, as indicated in Fig. 1. Note that there can be a different number of coupled models, $y_{c,i}$ than there are of subsystem models, $y_{s,i}$. The coupled model solvers are then used to obtain the final quantities of interest. In addition, there may be multiple levels of coupled models before arriving at the final quantities of interest, for example, one that might go from micro- to meso- to macro-scale behavior of a material.

Extending UQ activities to coupled models is not as straightforward as it is with numerical models that require only one forward calculation. Coupled simulations can be computationally more expensive to execute, and can be defined using different model forms or structures. For example, in the coupled model framework illustrated in Fig. 1, one can envision that uncertainty can be introduced using either the parameters at the subsystem level, $\theta_{s,i}$, or parameters at the coupled model level, $\theta_{c,i}$. In this sense, the numerical model can be defined using the subsystem level model form or the coupled level model form. At the subsystem level the parameters may have a physical meaning, such as material density or geometry, suggesting that UQ at this level will carry a physically meaningful interpretation. However, this approach may be cost prohibitive to perform due to the computational expense required to execute the subsystem models several times. In comparison, UQ at the coupled model level is computationally cheaper to perform but at the risk that the results will lose physical meaning.

One analysis that may be considered as a coupled model simulation is the Statistical Energy Analysis (SEA), and some of the alternative methodologies that have been inspired by SEA for studying the mid- to high-frequency vibration response of structures. SEA was first developed for application to satellite launch vehicles and has since been extended to other applications, for example the design of cars, trains, and satellites [1–4]. The goal of SEA is not to provide a high-fidelity simulation but rather to provide a statistical average of the vibratory behavior of the structure of interest [5]. The basic premise of SEA is to reduce a structure down to single degree of freedom (SDOF) oscillators that are analyzed through their subsystem responses. SEA offers computational efficiency by analyzing SDOF oscillators, however, this simplification comes at the cost of losing spatial resolution of the system response. The main assumptions needed for the analysis have been widely acknowledged [6] and include: (i) the need for a large population of modes in the frequency band of interest (contested in [7]), (ii) modal equipartition, meaning that no mode dominates the energy in the frequency band, (iii) the ratio of the coupling loss factor to the internal loss factor is low, (iv) coupling between subsystems must be conservative, and (v) excitation must be wide-band, spatially distributed and uncorrelated. Despite these assumptions, the method has been shown to work well in several applications, however, different aspects of the method have been questioned due to the numerous assumptions.

To remedy the assumption of modal equipartition an alternate approach known as the Statistical Modal Energy Distribution Analysis (SmEdA - the S, E, and A remain capitalized to emphasize its roots in the SEA approach) has been proposed [8–10]. SmEdA is one of several strategies developed to extend the statistical approaches to lower frequencies and tackle the mid-frequency problem such as the Asymptotic Scaled Modal Analyses based on scaling procedures [11,12], or the Energy Distribution Methods [13] that propose alternatives to compute the SEA parameters. SmEdA utilizes natural frequencies and mode shapes of the subsystems used to drive the analysis, rather than approximating the behavior of a structure using SDOF oscillators as is done in SEA. The natural frequencies and mode shapes are typically obtained through FE analysis, however, any form of analysis, experimental or analytic, can be utilized to provide modal information. When the