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A stochastic methodology for predictions of the environment created by multiple microvibration sources

M. Remedia [a],*, G.S. Aglietti [a], G. Richardson [b]

[a] *Surrey Space Centre, University of Surrey, Guildford GU2 7XH, UK*
[b] *Surrey Satellite Technology Limited (SSTL), Guildford GU2 7YE, UK*

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ABSTRACT

It is well documented that at frequencies beyond the first few modes of a system, the Finite Element Method is unsuitable to obtain efficient predictions. In this article, it is proposed to merge the efficiency of the Craig–Bampton reduction technique with the simplicity and reliability of Monte Carlo Simulations to produce an overall analysis methodology to evaluate the dynamic response of large structural assemblies in the mid-frequency range. The method (Craig–Bampton Stochastic Method) will be described in this article with a benchmark example shown and implemented in the theory of the dynamic coupling extended to the case when multiple sources of microvibrations act simultaneously on the same structure. The methodology will then be applied to a real practical application involving the modern satellite SSTL 300 S1.

1. Introduction

It is well known and documented that the Finite Element (FE) Method [1] gives accurate predictions for static analyses, and dynamics as long as the frequency does not exceed that of the first few structural modes of vibration [2], that is where the behaviour of physical structures is quite deterministic. However, increasing the frequency the behaviour of real structures becomes more sensitive [3], and even nominally identical structures can produce relatively different high frequency responses (this is particularly evident for complex structural assemblies). In this high frequency range statistical approaches are more suitable, and here Statistical Energy Analysis [4–6] (SEA) has been applied quite successfully [7–9]. Between low frequency and high frequency (i.e. in the mid-frequency) FE predictions start to become inefficient (good predictions could still be obtained, but building the appropriate detailed model would be extremely difficult and very demanding from a computational point of view), and SEA is not applicable as some of its basic assumptions are not yet validated.

The mid-frequency range is of particular interest in the study of spacecraft structures, and this work has been developed in the context of a project concerning analyses of transmission of microvibrations in satellites, but it is also applicable to many other fields, as long as the requirements described later on in the introduction are satisfied.

Abbreviation: FE, Finite Element; SEA, Statistical Energy Analysis; SFEM, Stochastic Finite Element Method; MCS, Monte Carlo Simulation; CMS, Component Mode Synthesis; CB, Craig–Bampton; CBSM, Craig–Bampton Stochastic Method; PSD, Power Spectral Density; SQM, Structural Qualification Model; RSS, Root Sum Square

* Corresponding author.
E-mail address: m.remedia@surrey.ac.uk (M. Remedia).

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With the term microvibrations we generally refer to accelerations in the region of micro g, and generally these low level mechanical disturbances occur over a wide frequency range, from "zero" up to say 500–1000 Hz. In addition to the issue of their control and minimisation [10–12], because of the large bandwidth of the frequency range, the modelling and analysis of micro-vibrations pose a challenge. This is a particular issue in the mid-frequency range as many of the micro-vibration sources on board a spacecraft (e.g. rotating mechanisms as reaction wheels, which are used to control the attitude of the satellite, or antenna pointing mechanisms) excite the structure in the mid-frequency range. In this case, besides the typical issues related to predicting responses in the mid-frequency, the low amplitude of the inputs can produce further uncertainties which can manifest themselves as nonlinearities. A typical example is the behaviour of cables secured onto panels [13–15] when very low forces are applied: the presence of the cables can influence the characteristics of the panel in terms of stiffness and damping values. The cables themselves become paths for vibration transmission and modelling them with simple non-structural mass (as it is often done for structural analyses) does not give accurate results.

Various approaches have been considered to solve micro-vibration analyses and mid-frequency problems in general. Many approaches can be found in MID-MOD [16]; here, finite element and statistical approaches (or both at the same time) are described. A literature review on a series of methods used to investigate the mid-frequency issue has been given by Desmet [2]. One of the most successful implementations described in the book is the hybrid method developed by Shorter and Langley [17,18]: the structure is divided into subsystems and some of them are described as finite element models, whilst others, which display a resonant behaviour, are studied with SEA. This method gives excellent results, providing the subsystems are appropriately selected. In the same context, also less recent works can be taken into account, such as Huiban and Baillion [19], who introduced the modal hybridisation. This method consists in building up responses given by the contributions of all the modes located in certain bands of the frequency spectrum. The drawback is that it strongly overestimates the response where modal overlap starts to be consistent.

One of the most classical types of approach used is to extend the range of validity of the FE method results to higher frequencies and to account for uncertainties in parameters affecting the dynamic responses. This group of methods, which often consists of some pre or post processing the data obtained from a FE analysis, is called Stochastic Finite Element Method [20] (SFEM). One of the most well-known analysis types is the Monte Carlo Simulation (MCS), which is the simplest method for treating the response variability calculation in the framework of SFEM. Here, a number of samples of the stochastic system are generated (i.e. perturbing some of the structural parameters), and for each one of them the equilibrium equation is solved in order to evaluate the response leading to a population of the response vectors. MCS gives the best (most realistic) results, and in fact it is often used as a benchmark to compare the performance of other methods [21,22], but it is still too computationally expensive, especially for large models of structures.

A considerable amount of research has been published on approaches aimed at reducing the computational effort spent for the analysis, most of them using classical reduction methods [23]. The Craig–Bampton (CB) reduction method [24] has been chosen for the work described in this article, for various reasons: it is particularly suitable for base shake analysis, such as the analysis of satellite structures supported by the launch vehicle; and, most importantly, it is used for the Component Modal Synthesis (CMS) [25], which is one of the key techniques utilised in this article. In addition, most FE models of specific satellite subsystems are delivered by subcontractors to the company that assembles the overall satellite structure in a reduced form (typically using CB reduction and therefore without giving any of the geometric and property details). For this reason it is difficult to implement a full MCS with perturbations of physical structural parameters for those specific components.

Amongst some of the proposed methodologies, Sarsri et al. [26] combined CMS and polynomial chaos basis to investigate the frequency transfer functions for large linear FE models of beams and assembled plates. A subspace iteration scheme has been developed by Pradlwarter et al. [27] to be used instead of CMS under specific circumstances. If uncertainties are in the joints [28] or in the boundaries [29] of the subsystems, CMS is the best approach for two reasons: the dynamic behaviour of the reduced structures is represented with just a few modal coordinates; the boundary degrees of freedom are still physical and therefore a MCS can still be applied using them. One of the most successful works developed in this context is the one published by Soize [30], which applies perturbations on the reduced matrices replacing the eigenvectors produced with mid-frequency energy eigenvectors.

In the context of robust dynamic condensation methods, a very interesting work has been developed by Guedri and Bouhaddi [31,32]: here, the stochastic surface method and the non-dominated sorting genetic algorithm are coupled to take into account the propagation of uncertainties in FE models. In addition, two modal approaches have been presented by Van den Nieuwenhof and Coyette [33] as an alternative to direct formulations for dynamic analysis of structures with random material and shape parameters. Elsewhere, the dynamic condensation has been approached from an iterative perspective [34].

In this article we propose a variation of the CMS to merge the efficiency of CB reduction with the simplicity and reliability of MCSs for the various subsystems to produce an overall analysis methodology. This approach (which for the sake of simplicity in this article will be called Craig–Bampton Stochastic Method, CBSM) is a good compromise between the simple mode superposition, which produces results which are not reliable after the first few modes of vibration, and a computationally expensive full MCS. This method therefore succeeds in both reducing drastically the computational effort involved and proposing an approach which can be easily implemented by well-known FE method software. Mace and Shorter [35] have proposed the concept for a method that estimates frequency response function statistics in structures with uncertain parameters using an approach involving CMS. However, as the perturbations were limited to the stiffness matrix, it was not able to perturb the characteristics of each subsystem mode, which on the other hand the full MCS does. In this