Virtual testing application to ESA micro vibrations measurement system

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Abstract. The challenging application of Virtual Testing (VT) to ESA's six-degree-of-freedom Micro Vibrations Measurement System (MVMS) is described in this work. The digital replicate of MVMS is first obtained from a high-fidelity finite element model, whose order is later appropriately reduced. A state-space model representative of the dynamic behaviour of the MVMS is finally obtained. MVMS VT simulations are thus exploited as a key enabling technology to perform the ad-hoc design of MVMS control system design. This work focuses on different model-order reduction techniques applied to MVMS, which were evaluated and compared in terms of performance and computational issues. Classical and more recent approaches belonging to the family of Component Mode Synthesis (CMS) methods are addressed. State-space based techniques are considered as well, also in two-stage combination with CMS methods. Challenges and advantages of VT are lastly discussed.

Introduction to MVMS and virtual testing methodology

MVMS is a novel 6DOFs microvibration facility developed for the European Space Agency (ESA) by the UK's National Physical Laboratory. It is designed to measure/impose microvibration accelerations, forces, and moments in the frequency range from 0.03 Hz to 100 Hz, thus allowing both the characterisation of potential microvibration source and the assessment of an item's performance subjected to a microvibration environment [1]. Figure 1 shows MVMS, which is composed of three main components: a base support (BS), the VIBration ISOlation platform (VIBISO), and the vibration Measurement PLatform (MPLAT). The base support interfaces with the ground, and it is mechanically connected to VIBISO through a MINUS-K device which acts as a passive mechanical low-pass filter. The function of BS is to sustain the upper MVMS components and to hold the seismometers and the fixed parts of the voice coil actuators, which form the set of sensors/actuators used by VIBISO to complement and improve the passive isolation provided by the MINUS-K with an active control action. Indeed, the aim of VIBISO is to actively isolate the upper part of the facility from vibrations transferred via the ground such as seismic disturbance. The function of MPLAT is to measure/impose the microvibration environment from/to the test specimen. It interfaces VIBISO through a second MINUS-K device and an additional set of voice coil actuators.

The digital replicate of MVMS is obtained by a properly correlated high-fidelity finite element model of the facility. A set of reduced-order models are later derived by retaining only the most relevant dynamics information, with the final aim of using the resulting state-space representation for the control system design. Figure 2 provides an overview of the computational methodology put in place for MVMS Virtual Testing in line with [2].

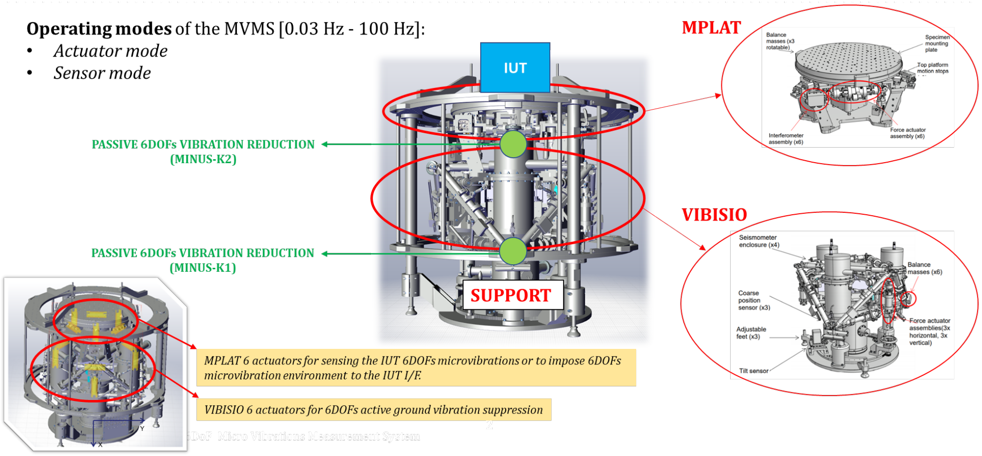

Figure 1. General description of the MVMS facility.

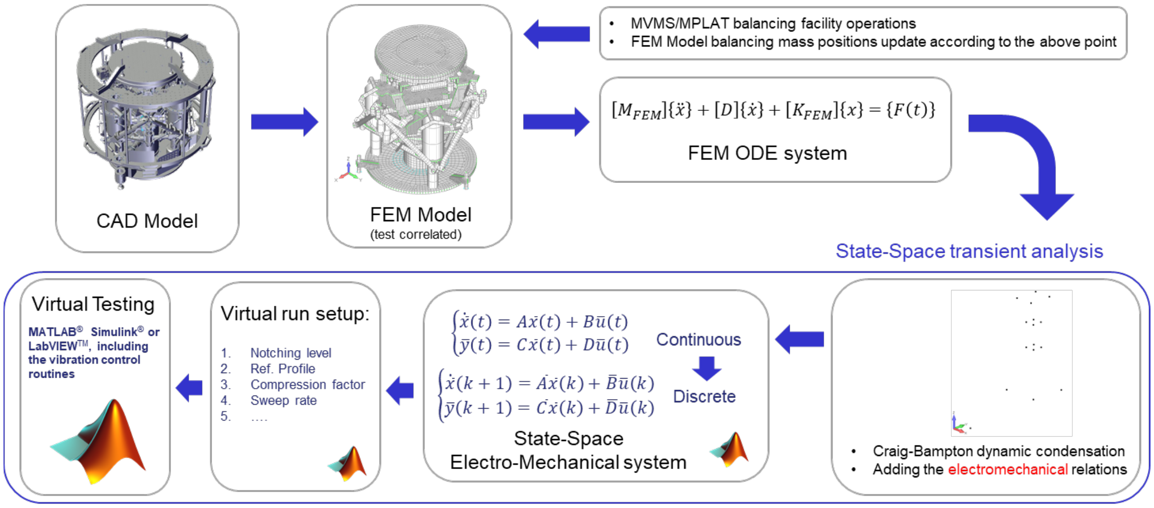

Figure 2. Overview of the computational methodology of MVMS Virtual Testing.

Assessment of model-order reduction techniques

In this work, several different model-order reduction techniques are considered, evaluated, and compared in terms of performance and computational issues. Classical and more recent approaches belonging to the family of Component Mode Synthesis (CMS) methods are applied to MVMS, as well as state-space based techniques such as the simple modal truncation (MT) and the powerful balanced truncation (BT). A hybrid technique consisting in a two-stage reduction combining CMS methods with BT or MT is also developed to overcome the numerical difficulties associated with the direct application of BT to very high-order problems [3]. A very restricted selection of results is presented below to give a concise comparison of the various methodologies, along with advantages or disadvantages of the adopted techniques.

Concerning CMS methods, in addition to the classical Craig-Bampton (CB) method [4], the Rubin (RU) method [5] and the Enhanced Craig-Bampton (ECB) [6] technique are evaluated. The reductions are carried out by considering as substructures the three main components of MVMS. Both ECB and RU aim to improve CB reduction performance by taking into account a contribution coming from discarded modes in the transformation matrix. While in RU this is achieved by approximating the dynamic behaviour via free-interface normal modes, ECB considers fixed-interface modes as in the original CB formulation. The selection of component modes to be retained for the three substructures is carried out by resorting to the Effective Interface Mass criterion [7], resulting in 15, 37 and 4 modes, respectively, for BS, VIBISO and MPLAT, along with 60 boundary DOFs.

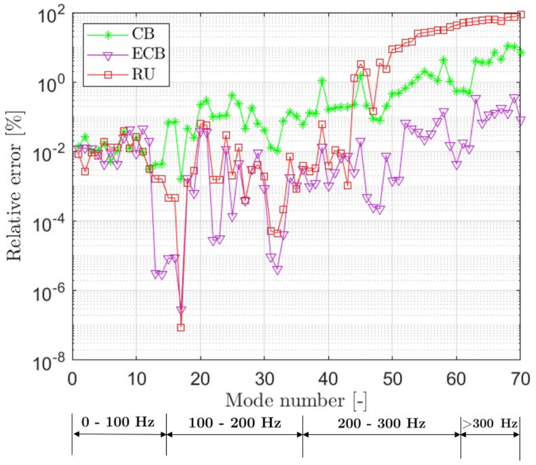

Figure 3. Relative error on natural frequencies among CMS methods.

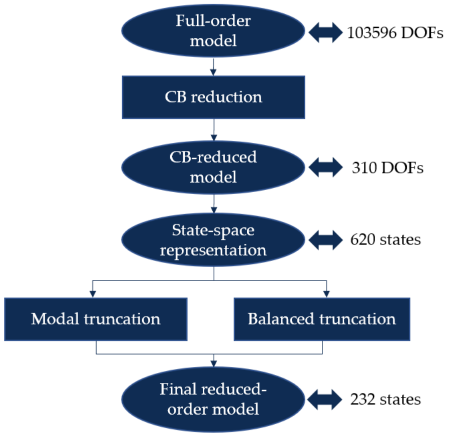

Figure 4. Two-stage reduction workflow.

Figure 3 reports the relative error between the natural frequencies computed by the high-fidelity FE model and those obtained from the reduced models. Both RU and ECB provide higher accuracy with respect to the classical CB reduction. In particular, ECB maintains superior performance in approximating both low and higher frequency modes, while a significant worsening is experienced with RU above approximately 250 Hz.

A similar analysis was carried out by employing MT and BT methods [8]. The latter is particularly appealing in the present VT approach, as it allows the input-output behaviour of the system to be preserved as much as possible. However, the high computational effort required by BT prevents its direct application to large-scale systems. This issue is overcome in this work by resorting to a hybrid two-stage reduction approach [9], envisaging a preliminary reduction via one of the CMS methods (CB is considered here), followed by either MT or BT, as reported in Fig. 4. The performance of the various reduction methods is assessed by comparing the frequency response in terms of the transmissibility from a longitudinal seismic disturbance to the item under test as shown in Fig. 5. All the methods, except for the hybrid MT, provide a high-performance approximation of the system response. The lack of a notable difference among the methods is explained by the peculiar dynamic behaviour of MVMS. Indeed, the low-pass filtering action of the MINUS-K devices strongly affects the dynamic response, which is dominated by a few low-frequency structural modes. With the aim of providing a deeper insight into the performance of the reduction techniques, the same analysis is carried out by retaining a significantly lower amount of DOFs. Figure 6 reports the relative error in the transmissibility function between the full-order and the reduced models. The largest improvements with respect to the classical CB method performance are provided by ECB and hybrid BT techniques.

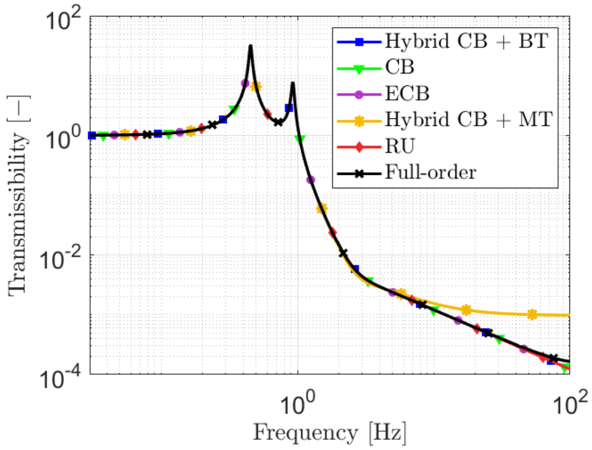

Figure 5. Comparison of the frequency responses.

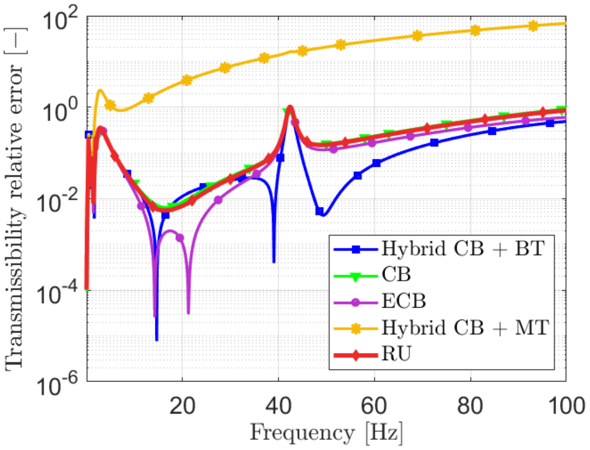

Figure 6. Relative error on the transmissibility.

In conclusion, referring to the MVMS application, hybrid BT and ECB appear as the most promising methods in terms of performance improvements with respect to classical reduction techniques typically adopted in the VT framework.

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