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An enhanced methodology for spacecraft correlation activity using virtual testing tools

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ABSTRACT

Test planning and post-test correlation activity have been issues of growing importance in the last few decades and many methodologies have been developed to either quantify or improve the correlation between computational and experimental results. In this article the methodologies established so far are enhanced with the implementation of a recently developed procedure called Virtual Testing. In the context of fixed-base sinusoidal tests (commonly used in the space sector for correlation), there are several factors in the test campaign that affect the behaviour of the satellite and are not normally taken into account when performing analyses: different boundary conditions created by the shaker's own dynamics, non-perfect control system, signal delays etc. All these factors are the core of the Virtual Testing implementation, which will be thoroughly explained in this article and applied to the specific case of Bepi-Colombo spacecraft tested on the ESA QUAD Shaker. Correlation activity will be performed in the various stages of the process, showing important improvements observed after applying the final complete methodology.

1. Introduction

Correlation between Finite Element (FE) model and physical flight/test model for spacecraft applications has been a subject of growing importance in the last few decades and increasing precision is needed as performance requirements from companies and launcher authorities for Coupled Load Analysis (CLA) are becoming more stringent [1]. A considerable amount of literature can be found on correlation activity, tackling the problem from two different perspectives: i) quantifying the level of numerical-experimental correlation, investigating what the most appropriate parameters are according to the specific applications and ii) improving the FE model so that computational simulations/analyses can better match experimental results.

On one side, updating methods have been developed and tested for decades [2,3]. More recently, a number of different strategies have been applied in the field to make the process faster and more accurate: examples are Genetic Algorithms [4], Hamiltonian Monte Carlo [5] and Component Mode Synthesis techniques [6,7]. On the other side, comparison techniques have also been undergoing significant research, but the common vector based techniques are still the most commonly used:

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examples are Modal Assurance Criterion (MAC) [8], Response Vector Assurance Criterion (RVAC) [9], Cross-Orthogonality Check [10] and Frequency Response Assurance Criterion (FRAC) [11].

The purpose of this paper is to improve the way we look at comparing the computational and the experimental data, which sometimes can be grossly misinterpreted. All the aforementioned techniques still stand, but it is crucial to ensure consistency between the test setup and the mathematical model, in particular when dealing with large structures as spacecraft can be. This can be taken care of with the implementation of a recently developed approach which goes under the name of Virtual Testing (VT).

VT is an approach used differently in several application fields, from aircraft [12], to automotive [13], to composites [14]. In most of these cases, the virtual approach is used as a substitution of the real physical test to avoid construction of expensive prototypes or to avoid time-consuming tests, such as fatigue. In this paper the VT approach is used for a different purpose, which is not avoiding tests, but it is to be used in conjunction (before or after) with the real test, as a support tool.

When running simulations, the current common practice, aimed at reproducing what happens in a vibration test facility, is to perform base-driven analyses (FE model of the structure constrained to the ground) applying accelerations at the base one translational degree of freedom at a time. This approach is most often flawed and, when dealing with larger structures as exciters, it is actually far from reality, because of the boundary conditions (the shaker or slip table is not infinitely stiff as it is supposed to be and it will inevitably have its own dynamic behaviour which couples with the structure under test at fairly low frequencies [15]) and the control system that is not perfect, resulting in delays and other effects, such as overshooting. In this context, VT means including all these dynamics into our computations, so that we know we are comparing results created by the same environment, which is fundamental for an accurate post-test correlation activity.

VT is a technique where the whole testing facility setup is modelled in its three components: the shaker (or slip table), the control system and, of course, the satellite structure. VT is a procedure that can be used either as pre- or as post-test activity; in fact, it allows: i) predicting data to understand projected test outcome in terms of boundary condition effects, test item control issues, avoid over-testing, deciding pilots' and other accelerometers' positions and more; ii) improving FEM correlation, i.e. developing a validated FE model where test hardware influences, boundary condition effects or shaker control influences may be "filtered out" to obtain a mathematical model devoid of such test hardware influence and therefore more suitable for the validation of the satellite FE model.

A few implementations of virtual testing procedures are presented in the literature. Liu, Xiang et al. [16,17] divided the facility into five different subsystems (control system, power amplifier, shaker, acceleration transducer and filter/amplifier) proving how close results are comparing the computational outcomes with the real test data. Ricci, Peeters et al. [18] showed the need for a VT extension of the computational activity using the ESA QUAD shaker [19] as test case, a prelude of the activity described in this article.

Here a novel methodology for the use of VT as a tool for post-test correlation activity is developed. In addition, the VT approach is for the first time applied to the test campaign of a very large spacecraft, Bepi-Colombo [20] on the ESA QUAD shaker, and used to successfully prove the validity of the novel methodology. In particular, Section 2 describes in general terms the aforementioned methodology. In Section 3 an overview of the correlation parameters chosen for this study is given. Section 4 presents the Bepi-Colombo satellite and the correlation activity pre-VT. Section 5 provides a description of the VT procedure before being applied to the specific test case in Sections 6 and 7.

2. Methodology

The current practice for correlation activity is grounding the FE model of the spacecraft and imparting excitations at the base with the same level as the ones used during the test campaign, one translational degree of freedom at a time. FRFs are then computed and these are compared to the experimental measurements using indicators such as MAC, FRAC, RVAC etc. If the correlation shows that the model responses are significantly different from the computational results (specific thresholds are given by launch authorities and Agencies), a process of model updating is started and computational analyses are re-run until a good agreement is reached and the validated FE model can be used for further analysis, such as CLA. This whole process can be summarised with the block diagram of Fig. 1.

The issue with the procedure shown in Fig. 1 is that there are several environmental factors (mainly boundary conditions) during the test campaign which have a very significant influence on the measurements provided by the sensors placed on the spacecraft. These factors include the dynamics of the shaker, the control system and other elements, such as delays that can be observed, for instance, from the moment the signal is produced and the moment the input is actually provided to the actuators. The direct consequence is that the spacecraft is not actually behaving anymore as if it is actually grounded and the output signals are not exclusively related to the input provided as it happens for computational analyses using finite elements.

In common industrial practice, it is known that shaker dynamics may affect the fundamental modes of the spacecraft, and this is addressed introducing flexibility at the base of the structure, where it is connected to the shaker (or slip table). In this paper, though, it will be shown how the shaker dynamics, in conjunction with non-perfect control and other environmental factors, significantly affect the test results and therefore the test item behaviour across the whole frequency spectrum, proving the reproduction with simple springs to be too simplistic [21].

There are two solutions that can be adopted in these circumstances. The more logical one would be to fix the issues related to the test facility, but this is an extremely difficult task which is likely to be not viable with the technology at