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A minimum drives automatic target definition procedure for multi-axis random control testing

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ABSTRACT

Multiple-Input Multiple-Output (MIMO) vibration control tests are able to closely replicate, via shakers excitation, the vibration environment that a structure needs to withstand during its operational life. This feature is fundamental to accurately verify the experienced stress state, and ultimately the fatigue life, of the tested structure.

In case of MIMO random tests, the control target is a full reference Spectral Density Matrix in the frequency band of interest. The diagonal terms are the Power Spectral Densities (PSDs), representative for the acceleration operational levels, and the off-diagonal terms are the Cross Spectral Densities (CSDs). The specifications of random vibration tests are however often given in terms of PSDs only, coming from a legacy of single axis testing. Information about the CSDs is often missing. An accurate definition of the CSD profiles can further enhance the MIMO random testing practice, as these terms influence both the responses and the shaker's voltages (the so-called *drives*). The challenges are linked to the algebraic constraint that the full reference matrix must be positive semi-definite in the entire bandwidth, with no flexibility in modifying the given PSDs.

This paper proposes a newly developed method that automatically provides the full reference matrix without modifying the PSDs, considered as test specifications. The innovative feature is the capability of minimizing the drives required to match the reference PSDs and, at the same time, to directly guarantee that the obtained full matrix is positive semi-definite. The drives minimization aims on one hand to reach the fixed test specifications without stressing the delicate excitation system; on the other hand it potentially allows to further increase the test levels. The detailed analytic derivation and implementation steps of the proposed method are followed by real-life testing considering different scenarios.

1. Introduction

Vibration control tests are performed to verify that a system and all its sub-components can withstand the vibration environment during the operational life. These tests aim to accurately replicate via controlled shaker excitation the in-service

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structural response of a unit under test in the main axis of vibration and in all the possible axes where the levels exceed the acceptance thresholds [1]. The simplest way to expose a test article to an excitation in multiple axes is to perform a sequential Single-Input Single-Output (SISO) test: sequentially, the test article is rotated, the test set-up changed and a new test is performed with the required SISO profile as test specification. Practical aspects, linked for instance to the sizes of the article to be tested or to issues in changing multiple times the test set-up [2], can make the execution of these tests challenging or even impossible. However, the most critical aspect of a sequential SISO test is that it poorly represents any real vibration environment and therefore can lead to an unacceptable time to failure estimation for the unit under test and different failure modes [3]. This has been shown in small-scale problems, such as printed wiring boards testing (where the inductor are critical components) [4] or thin plates [5], but also in large-scale tests, such as large spacecraft vibration testing as shown in [6]. The only alternative to overcome the sequential single-axis test limitations is to apply a simultaneous multi-axial excitation performing a Multi-Input Multi-Output (MIMO) vibration control test [7–9].

Even though the benefits of MIMO testing are clear and widely accepted by the environmental engineering community, ever since 1958 (the first documented attempt to simultaneous multi-axial excitation [10]), this practice experienced a very slow growth. Initially this was due to the available technology in terms of excitation mechanisms and computational power for the data acquisition hardware and vibration controllers. The first multi-input control algorithm was developed only twenty years later, in 1978 by David Smallwood from Sandia National Laboratories (as documented in the 1982's publication *A Random Vibration Control System for Testing a Single Test Item with Multiple Inputs* [11]) and coped with the available computational power. Modern MIMO vibration control strategies rely on the work of Underwood [12], whose first patent on the topic is dated 1994 [13]. Just recently, the increased complexity, sizes and cost of the article to be tested increased the concern about replicating as close as possible the environments to be tested [2,14–18]. The high degree of expertise needed to perform these tests and decades of single axis controlled excitation built meanwhile a legacy of SISO standards that currently represent the main reference for the environmental test engineers. For these reasons nowadays MIMO vibration control tests are still considered as a *pioneering* testing methodology.

There are different types of MIMO tests (random, sine, time waveform replication), depending on the environment a test article needs to be exposed. For automotive and aerospace systems and subsystems, a random vibration test is required for all the main mechanical and electrical components [19]. This type of test is performed to simulate the response of the unit under test to a broadband random Gaussian vibration environment. Typical scenarios are the road excitation or the response to a diffuse acoustic field [20]. For the SISO case the test specification is a Power Spectral Density (PSD, usually in g^2/Hz) profile that needs to be replicated for a user-defined control channel by exciting the unit under test with a single-axis shaker. In the MIMO case, it is possible to define required test levels for multiple control channels that will be controlled simultaneously. Additional information about the cross-correlation between the control channels is also included. This information must be provided in terms of Cross Spectral Densities (CSDs) between pairs of control channels defining desired phase and coherence profiles [8,9,14]. The definition of these terms is essential to also replicate the cross-correlation that naturally exists between difference responses. These terms are also controlled by modern vibration controllers. For these systems the control target is thus a full reference Spectral Density Matrix (SDM). The target definition process plays already a key role for MIMO random control tests as documented in recent studies [21–24].

Theoretically, a successful MIMO random control test can be performed in case the operational environment is fully replicated in the laboratory, meaning that

1. the nature of the operational loads can be exactly replicated with the available exciter(s);
2. the boundary conditions can be also exactly replicated with the available fixtures;
3. operational measurements are available for all the control points.

In the last years significant works have been published that focus on the excitation and boundary conditions replication on the test results. The works of Daborn [17,25] on aerodynamically excited structures show how increasing the number of control channels and trying to match the operational mechanical impedance, on top of a successful random test, also allows to closely match the response in location that are not controlled. These observations are at the basis of the so-called *IMMAT (Impedance-Matched Multi-Axial Test)* approach [26]. Roberts in [18] shows that the (known) environmental replication further improves by increasing the number of shakers and adopting rectangular control strategies. The approaches require fully available operational measurements. As pointed out in [2], unfortunately operational measurements are not always available and often the test specifications are provided just in terms of PSDs at the control locations. This is due to several reasons. First of all, the gradual transition from sequential SISO testing to simultaneous multi-axial testing needs to face the aforementioned legacy of SISO standards and specifications, provided in terms of PSDs. Second, the standardization of the CSD terms is impractical to implement in a specification due to a lack of knowledge that makes challenging (and even impossibile) to average, smooth or envelope coherence and phase information from different operational conditions. In this case, the choice of setting appropriate values to fill in the full reference matrix *must reflect the desires of a knowledgeable environmental test engineer* [2]. Defining the reference matrix with no a priori knowledge of the cross-correlation between control channels is very challenging. Filling in the off-diagonal terms, in fact, must guarantee that the reference matrix will have in the end a physical meaning (realizable). This is translated in the algebraic constraint that this matrix needs to be positive semi-definite and at the same time the test needs to guarantee the required PSDs at the control locations.