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Virtual Shaker Testing: A Real-Time Framework for Predicting Spacecraft Vibration Tests

Mattia Dal Borgo[1], Umberto Musella[1], Laurane Thielemans[1], Silvia Vettori[1], Alberto G. de Miguel[1], Roland Pastorino[1], *Emilio Di Lorenzo[1], Bart Peeters[1]

[1]Siemens Industry Software NV, Interleuvenlaan 68, 3001 Leuven, Belgium

ABSTRACT

Dynamic testing of spacecraft and other critical aerospace structures is an essential process to ensure their structural integrity under operational loads, particularly those experienced during launch and ascent. Such tests aim to replicate the harsh vibratory environments that spacecraft must endure, providing direct evidence of hardware robustness and reliability.

However, the practical execution of vibration environmental tests presents significant challenges. One of the most critical issues arises from the dynamic interaction between the device under test (DUT), the vibration controller, and the shaker facility itself. In practice, the dynamics of the test facility, including the shaker, supporting structures, and interface hardware, often couple with the dynamics of the DUT within the frequency band of interest. This unintended coupling can compromise several aspects of the test: it can reduce the controller's ability to accurately replicate the target acceleration or displacement profiles, introduce artifacts or unexpected resonances in the test response, and ultimately degrade the correlation between measured test data and numerical simulations.

To mitigate these challenges and improve both test reliability and predictive accuracy, the concept of virtual shaker testing has emerged. A virtual shaker test acts as a real-time digital twin of the physical test setup. It enables engineers to simulate the entire closed-loop system, including the DUT, test facility, and controller, before conducting the actual physical test. This approach provides several advantages: it helps identify potential issues in test configuration, guides the selection of appropriate control strategies, and reduces the number of iterations needed to achieve test objectives.

This paper presents a structured methodology for implementing a virtual shaker testing framework, leveraging state-space modelling, dynamic sub-structuring, and real-time simulation technologies. The methodology comprises several key stages:

<u>1. State-Space Model Development</u>

A central step in building the virtual test is to develop an accurate, computationally efficient dynamic model of the coupled system. This model can be derived in two ways. The first approach involves conducting experimental system identification of the entire DUT and shaker facility assembly, and then representing the dynamic behavior using a modal synthesis approach fitted into a state-space form. The second approach leverages frequency-based dynamic sub-structuring to combine independently developed models of the DUT and the shaker system. In

this way, engineers can reuse detailed FEMs or experimentally identified sub-models of the DUT and test facility, resulting in a flexible modelling strategy adaptable to different test setups.

2. Real-Time Simulation Platform Integration

Once the state-space model is established, it is deployed onto a real-time simulation platform capable of running the model with low latency. The real-time platform interfaces with the vibration controller through analogue input-output (I/O) modules. This configuration mirrors the actual physical test arrangement, where the controller drives the shaker system using sensor feedback (e.g., from accelerometers on the DUT). By maintaining the same signal paths and timing constraints, the virtual test closely replicates the dynamic and control characteristics of the physical test.

3. Closed-Loop Virtual Test Execution

In this closed-loop configuration, the vibration controller operates as it would during the actual test, but instead of actuating the physical shaker and measuring the DUT response, it interacts with the real-time simulated model. This allows engineers to assess how the controller responds to the coupled dynamics, explore the impact of different control strategies (e.g., notching or tuning of control parameters), and identify potential issues such as transient overshoots, resonance amplification, or controller saturation. By predicting these behaviors before test execution, the setup can be refined and this will improve confidence in test results.

4. Validation and Correlation with Physical Tests

Following the execution of the virtual test, its results are systematically compared against measurements from the physical vibration test. This comparison serves multiple purposes: it validates the accuracy of the virtual model, reveals modelling gaps or parameter uncertainties, and improves the correlation between simulations and real-world data. By iteratively refining the model based on these comparisons, engineers can build highly reliable predictive tools for future test campaigns.

A key advantage of using a time-domain, state-space model is its ability to capture transient behaviors that can occur during vibration tests, especially during start-up, shutdown, or when control parameters change. These transient phenomena are often critical for test safety and performance, yet difficult to predict using frequency-domain methods alone.

In summary, the proposed virtual shaker testing framework combines experimental system identification, dynamic sub-structuring, real-time simulation, and closed-loop testing to create a powerful predictive environment. This approach enhances the planning and execution of dynamic qualification tests, reduces the risk of test anomalies, and strengthens the correlation between numerical models and physical measurements. As spacecraft designs become increasingly complex and test requirements more stringent, virtual shaker testing stands out as a practical, cost-effective tool to improve confidence in structural verification and reduce program risk.

Keywords:

Virtual shaker testing; spacecraft vibration test; real-time simulation; state-space modelling; dynamic sub-structuring; system identification; vibration controller; digital twin; structural dynamics; qualification testing