Chapter 10
Structural Response Characterization under Multi-Axis Excitation via Video Motion Magnification

Davide Mastrodicasa, Alberto Garcia de Miguel, Andrea Cavagnolo, Ruben Araujo, Umberto Musella, Emilio di Lorenzo, and Enrico Zappino

Abstract Vibration control testing aims at reproducing the dynamic environments that a component is expected to withstand in operation. These tests, typically conducted on shaker platforms, allow engineers to validate the survivability of hardware against severe vibration conditions. Recent advances enable excitation of components in multiple directions simultaneously using multi-axis shaker platforms controlled by advanced multiple-input multiple-output (MIMO) algorithms, thus simulating realistic dynamic environments. Pre-test activities are always conducted to ensure the feasibility of the test and optimize the setup and control parameters. However, the limited availability of sensors, coupled with time constraints, often leads to insufficient pre-test structural analysis. Such analyses could help identify critical responses or couplings with the shaker platform. This work proposes the use of Video Motion Magnification (VMM), a non-intrusive optical method based on video post-processing, to characterize structural responses. A novel aspect is the integration of synthetic image generation in Blender to anticipate the performance of the available cameras, whose noise floor is usually much higher than that of accelerometers. By replicating the setup in Blender, the feasibility of displacement retrieval through VMM can be verified before real testing. This two-step workflow is then applied in a laboratory pre-test, validating its capability to identify critical structural responses on a 3D printed CubeSat model.

Keywords Video motion magnification · Modal analysis · Pre-test · Vibration control · Optical methods

Introduction

Vibration qualification tests play a critical role in aerospace and mechanical engineering, ensuring that components survive harsh launch and operational environments. Traditionally, tests have been performed with sequential single-axis excitations, but the introduction of multi-axis shakers and MIMO control allows simultaneous excitation, offering a more realistic reproduction of in-service conditions [1].

Pre-test analyses are intended to optimize setup, refine control parameters, and anticipate dangerous resonances. In practice, though, they are often limited due to short campaign times and the difficulty of instrumenting small or inaccessible components with accelerometers. Non-contact optical methods provide a potential solution: Video Motion Magnification (VMM) can reveal otherwise invisible deformations by amplifying small motions in video recordings [2–4]. Despite its promise, the adoption of VMM in pre-tests is hampered by the relatively high noise floor of cameras compared to traditional sensors. This raises the question: can structural displacements expected in multi-axis tests actually be resolved with available imaging equipment?

Davide Mastrodicasa · Alberto Garcia de Miguel · Andrea Cavagnolo · Ruben Araujo · Umberto Musella · Emilio di Lorenzo
Siemens Industry Software NV, Interleuvenlaan 68, Leuven, 3001, Belgium
e-mail: davide.mastrodicasa@siemens.com; alberto.garcia_de_miguel@siemens.com; andrea.cavagnolo.ext@siemens.com; ruben.araujo@siemens.com; umberto.musella@siemens.com; emilio.dilorenzo@siemens.com

Andrea Cavagnolo · Enrico Zappino
Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy
e-mail: andrea.cavagnolo.ext@siemens.com; enrico.zappino@polito.it

Kristin B. Zimmerman, PhD (eds.), *Dynamic Evironments and Durability Testing, 2026, Vol. 7*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-8-743-81446-7_10

To address this challenge, we propose a two-step framework. The first step introduces synthetic image generation in Blender, a rendering and simulation tool, to act as a proof of concept. By replicating the test setup in a virtual environment, animating structural responses from numerical simulations, and applying VMM to the rendered videos, it is possible to determine in advance whether the chosen camera configuration is theoretically capable of resolving the displacements of interest. In this paper, this stage does not serve as direct validation against the physical experiment, but rather as a feasibility study to demonstrate the potential of the approach.

The second step applies the same optical configuration in the real laboratory pre-test, where low-level multi-axis excitation is introduced, and VMM is used to extract modal parameters and operational deflection shapes. Together, the virtual feasibility study and the real pre-test establish a practical pathway for incorporating optical methods into vibration campaigns, strengthening pre-test reliability and reducing the risk of unsuccessful measurement campaigns.

The proposed workflow is demonstrated through a vibration test campaign conducted on a multi-axis testing platform available in the Siemens facilities at Leuven, Belgium. The device under test (DUT) was a composite CubeSat made of PEEK material, manufactured by Politecnico di Torino, Italy, using 3D-printing techniques.

Methodology

The proposed methodology integrates numerical simulation, virtual imaging, and physical experimentation into a unified pre-test framework:

1. **Numerical Predictions:** Structural responses are estimated via finite element (FE) models under representative aerospace vibration profiles, which are generated in the software Simcenter 3D. The displacement fields are exported to provide input for the virtual stage.
2. **Virtual Pre-test in Blender:** The CubeSat model, fixture, and camera setup are replicated in Blender. The FE displacements are animated, and synthetic videos are rendered under realistic optical and lighting conditions.
3. **VMM on Synthetic Videos:** The rendered sequences are processed using phase-based VMM. This stage serves as a proof of concept to determine whether the expected displacements can be resolved above the simulated camera noise floor, guiding camera placement and acquisition parameters.
4. **Experimental Pre-test:** The validated configuration is transferred to the laboratory. The CubeSat demonstrator is mounted on a multi-axis shaker, excited under low-level broadband input using the control software Simcenter Testlab MIMO Random Control, and recorded using the high-speed camera. The videos are processed with the same VMM pipeline to extract modal parameters and operational deflection shapes.

This two-step framework ensures that optical measurements are not only theoretically feasible but also practically applicable in real test environments, reducing uncertainty and de-risking vibration campaigns.

Synthetic Image Generation and Virtual Test

Blender was employed to perform a virtual pre-test replicating both the specimen and the test environment. The geometry of the CubeSat demonstrator was modeled and imported into Blender, where the dynamic response obtained from FE simulations was animated. This enabled direct visualization of the expected mode shapes and displacement fields under low-level excitation.

Figure 1 illustrates the FE model of the structure mounted on the multi-axis platform, including the actuators that provide excitation along different directions. In the numerical campaign, the structure was excited using a power spectral density (PSD) profile representative of typical aerospace vibration environments, based on the VEGA C specifications, ensuring realistic loading conditions. The transient dynamic analysis provided the time histories of nodal displacements across the component. These displacement fields were then exported in a format suitable for post-processing and subsequently imported into Blender, where they served as the basis for generating synthetic video sequences of the vibrating structure.

To replicate laboratory conditions, the geometry was textured and rendered, as shown in Figure 2. The texturing step was not only meant to provide a more realistic appearance of the CubeSat structure, but also to introduce visual contrast features that enhance the detectability of small displacements during Video Motion Magnification. Smooth, uniform surfaces can often limit the sensitivity of optical methods, whereas patterns, grey scale variations, or surface textures allow the algorithm to track the displacement field. The resulting rendered model, therefore, supported both the aesthetic realism of synthetic videos and the technical requirement of making subtle vibrations visible once magnified.

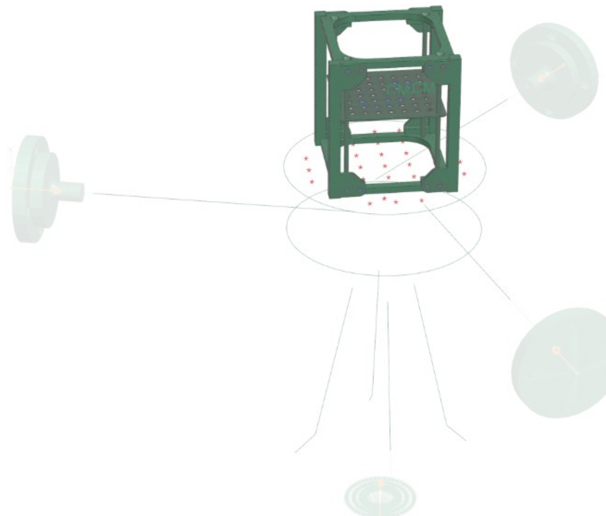

Fig. 1 Finite element model of the CubeSat demonstrator mounted on the multi-axis shaker platform, showing the actuators used for excitation

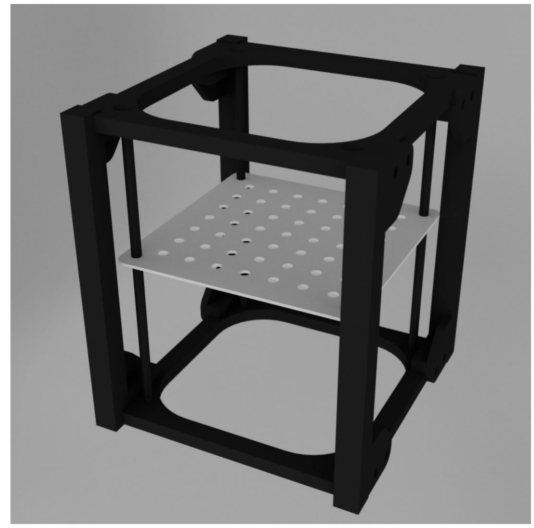

Fig. 2 Rendered CubeSat model with texture applied, used for generating synthetic video sequences

The rendered videos were subsequently processed using the phase-based Video Motion Magnification pipeline. The virtual test revealed whether the expected displacements could be resolved above the camera noise floor. This virtual pre-test therefore acted as a risk-free proof of concept, guiding the choice of optical parameters and acquisition settings for the real campaign. The virtual test was then carried out by exciting the structure up to 400 Hz. Synthetic cameras operating at a sampling rate of 800 Hz were used to record the response. The motion magnified videos were post-processed to extract the modal parameters of the structure. Using the Polymax algorithm [5], the natural frequencies and damping ratios were identified directly from the optical data. Subsequently, Operational Deflection Shapes (ODSs) corresponding to the identified natural frequencies were reconstructed, providing a clear visualization of the dominant vibration patterns. The first ODS, reported in Figure 3, corresponds to the first plate bending mode of the CubeSat panel, while Figure 4 shows the ODS associated with the second plate bending mode. These results confirm that the synthetic videos generated in Blender, once processed with VMM, can resolve structural responses with sufficient clarity to support optical measurements in vibration testing.

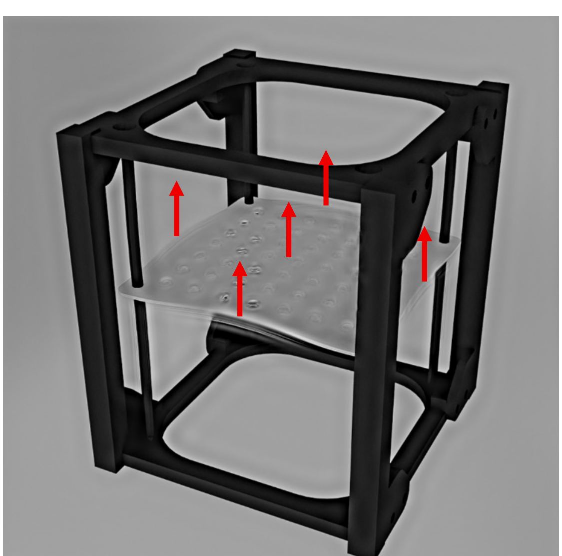

Fig. 3 ODS related to the first plate bending mode

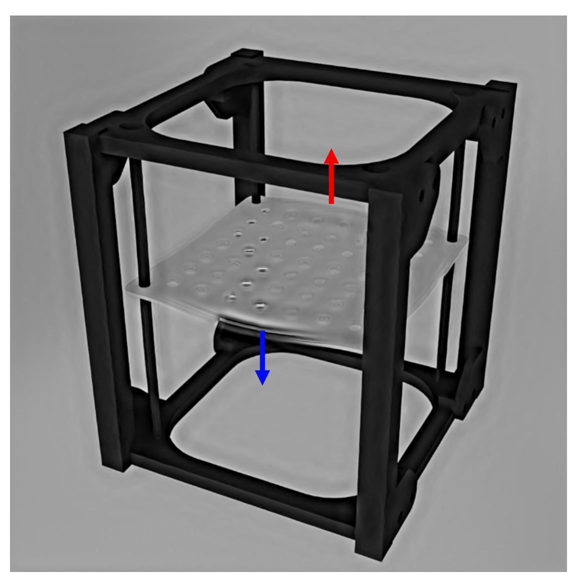

Fig. 4 ODS related to the second plate bending mode

Experimental Pre-test

The feasibility study carried out in the virtual environment was followed by a laboratory pre-test, designed to acquire real optical data of the CubeSat demonstrator under controlled excitation. The specimen was mounted on the multi-axis shaker platform and subjected to a broadband random excitation defined by the same PSD profiles in the 3 directions, consistent with qualification standards. Figure 5 shows the responses at the control locations against the reference profiles, indicating that the MIMO control test was successful.

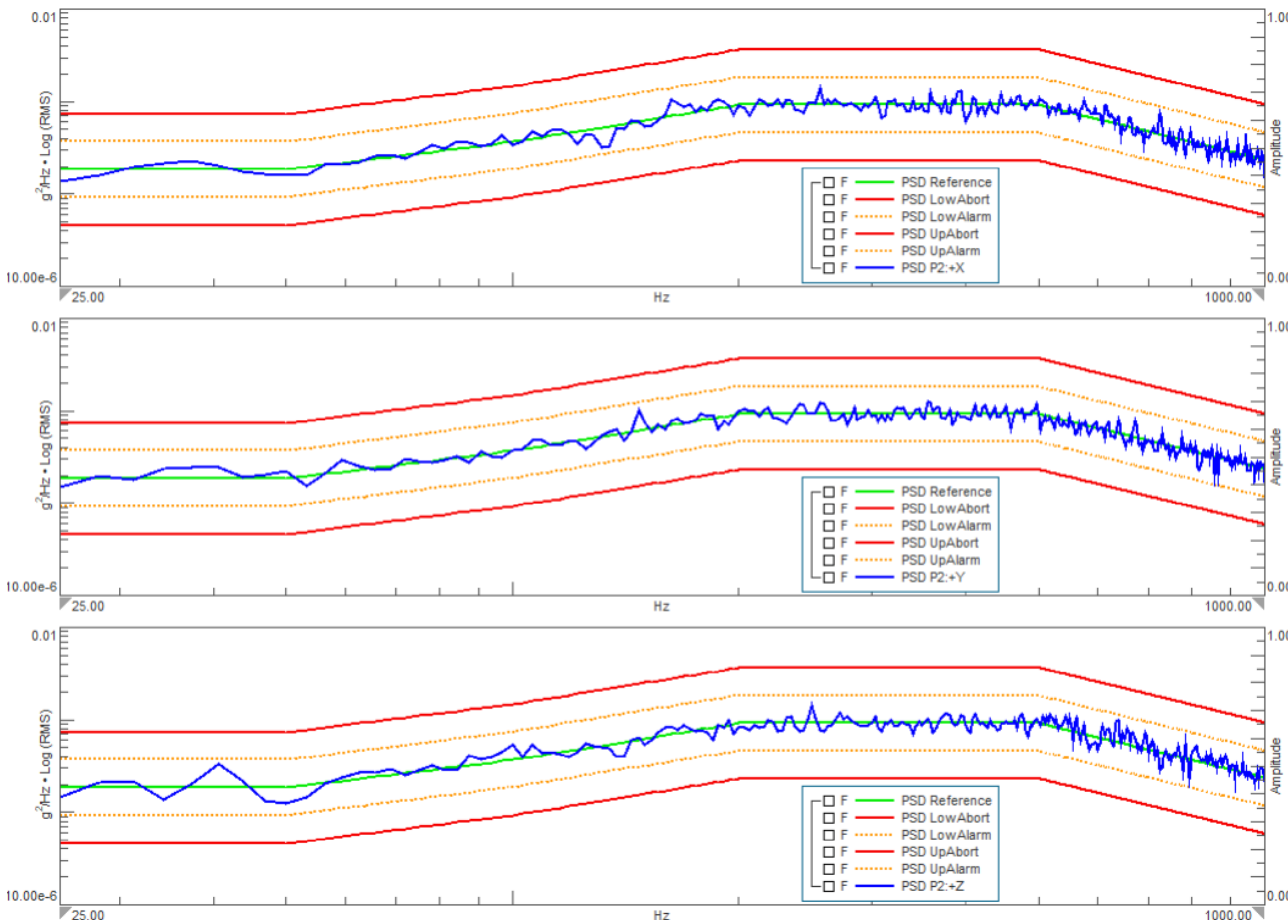

Fig. 5 PSD profiles used in the multi-axis shaker platform at the Siemens facilities in Leuven, Belgium. The blue lines are the acceleration PSD measured at the control sensors

A single high-speed 2 MPx iX i-SPEED 5 Series camera was positioned to reproduce the same point of view adopted in the synthetic image generation part. The camera operated at a sampling frequency of 1600 Hz, ensuring that vibration content up to 800 Hz could be resolved with adequate fidelity. Lighting conditions were optimized to minimize noise and enhance surface contrast, thereby improving the effectiveness of the Video Motion Magnification pipeline. An example of the recorded footage is shown in Figure 6.

The acquired sequences were processed using the same phase-based VMM algorithm employed in the virtual test. From the magnified motions, cross-power spectra were estimated, and the modal parameters, natural frequencies and damping ratios, were extracted using the Polymax method. The Cross Power Sum (CPS), reported in Figure 7, provides a frequency-domain overview of the global vibrational energy. The peaks in the CPS clearly indicate the locations of the main resonances.

Finally, the ODSs reconstructed at the identified resonances are shown in Figures 7 and Figure 8, corresponding respectively to the first and second plate bending modes of the CubeSat structure. These ODSs demonstrate that, even with the inherent noise floor of the optical acquisition, the structural dynamics of the component can be successfully resolved through video-based analysis.

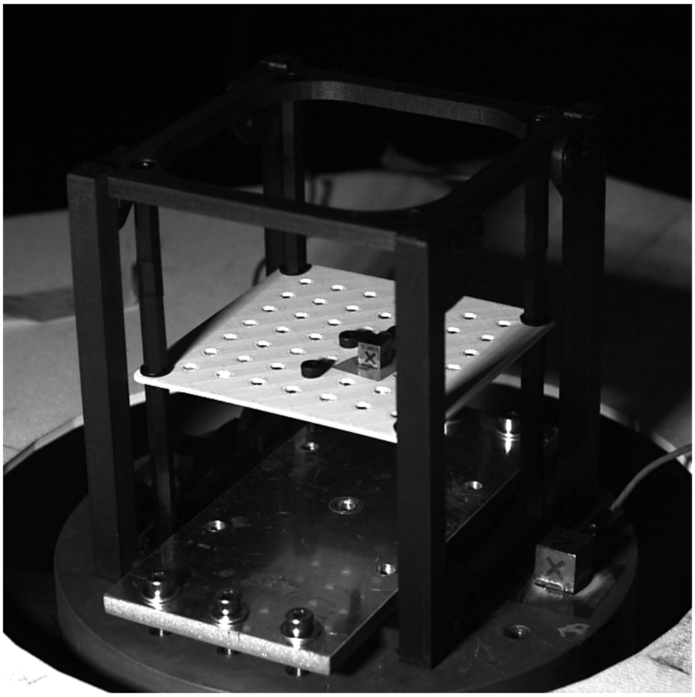

Fig. 6 Real footage

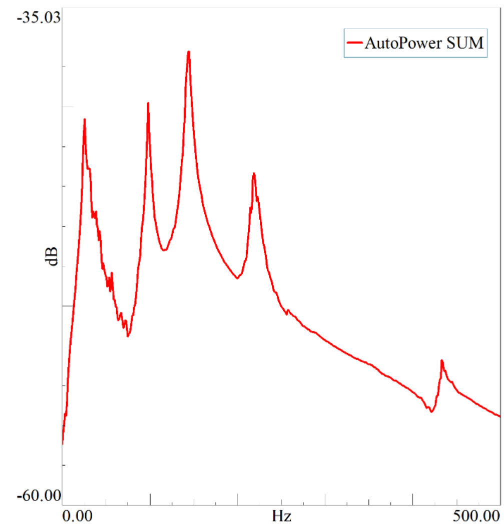

Fig. 7 Cross Power Sum

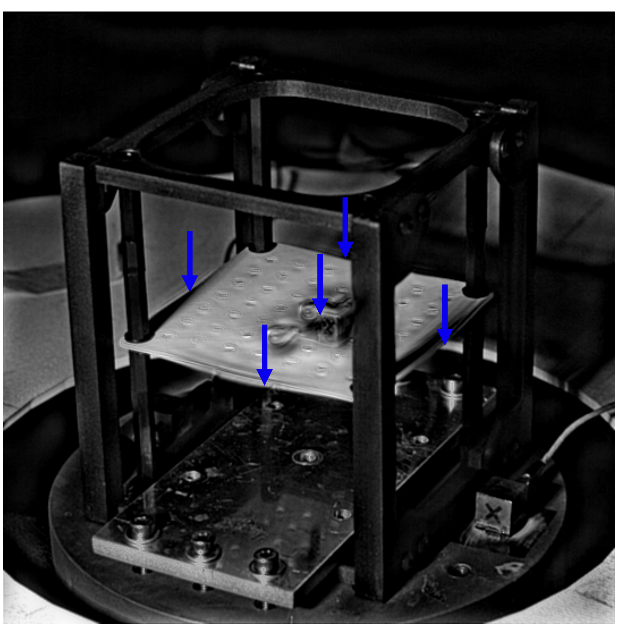

Fig. 8 ODS corresponding to the first plate bending mode, obtained from VMM-processed videos

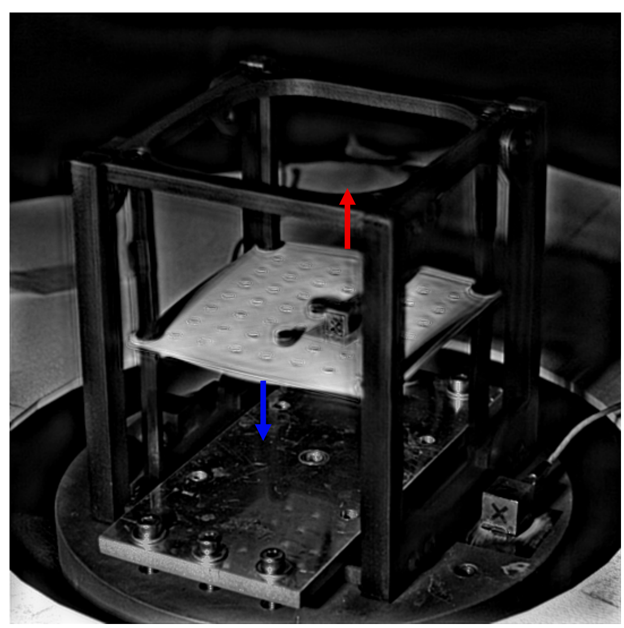

Fig. 9 ODS corresponding to the second plate bending mode, obtained from VMM-processed videos

Conclusion

This work presented a two-step methodology for structural response characterization for vibration control using video motion magnification. The first stage introduced a synthetic image generation workflow in Blender, where finite element displacements were animated and processed through VMM. This step served as a feasibility study to optimize camera placement and acquisition parameters, ensuring that the expected structural responses could be made optically detectable despite the higher noise floor of cameras compared to conventional sensors.

The second stage applied the methodology in a laboratory pre-test, where a CubeSat demonstrator was subjected to a controlled vertical excitation. High-speed video acquisition, followed by VMM processing, enabled the extraction of modal parameters and the reconstruction of operational deflection shapes. The results confirmed that optical methods can provide valuable insight into structural dynamics in a non-intrusive manner.

Together, these two stages establish a practical pathway for the use of video-based techniques in vibration test campaigns. The synthetic stage reduces risk by guiding the optical configuration and verifying feasibility in advance, while the experimental stage provides real-world confirmation of the method's applicability. This combined approach supports safer, more efficient test campaigns and offers a complementary tool to conventional sensor-based measurements.

Future work will aim at extending the methodology to more complex assemblies, improving displacement quantification, and further automating the integration between numerical simulations, synthetic video generation, and experimental testing.

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