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Advancements in structural dynamics characterization: the role of Video Motion Magnification in full-field Operational Deflection Shape characterization

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ABSTRACT

Emerging optical techniques such as digital image correlation, optical flow, and video motion magnification (VMM) are revolutionizing the characterization of structural dynamics by enabling full-field data collection. These methods provide spatially dense sensory data, surpassing traditional point-based sensors like accelerometers, and serve as valuable inputs for operational modal analysis (OMA).

VMM stands out as an effective standalone application for visualizing operational deflection shapes (ODSs) using a single camera. It demonstrates increased robustness against noise, although this comes with enhanced computational complexity due to the large volume of data generated. This study highlights VMM's potential in capturing power spectral density and ODSs of vibrating structures under various types of excitations, including acoustic, shaker, and environmental.

This paper presents vibration measurements from different industrial structures, such as full-scale aircraft ground vibration testing (GVT) and full-scale satellite subjected to Direct Field Acoustic Testing (DFAN). Additionally, in this work, the challenges of data management are discussed and a strategy for achieving full-field VMM-based OMA is discussed.

Keywords: Video Motion Magnification, Operational Deflection Shapes, Optical Methods, Vibrations

1. INTRODUCTION

The study of structural dynamics has significantly evolved in recent years, particularly with the integration of optical techniques such as digital image correlation (DIC), optical flow, and video motion magnification (VMM). These advancements have enabled precise, high-resolution measurement of displacement and strain in structures experiencing dynamic loads. Among these methods, DIC has proven highly effective in analyzing material behavior, offering

valuable insights for optimizing structural performance under different conditions. The continuous refinement of computational algorithms has further strengthened DIC's role as a crucial tool for engineers and researchers [1,2].

Accurate assessment of structures subjected to dynamic forces is essential across multiple industries, including aerospace, automotive, and civil engineering. Traditional sensors like accelerometers and strain gauges remain widely utilized, yet optical methods present key benefits, such as full-field measurement capabilities, improved resistance to noise, and non-contact operation, minimizing potential damage to test specimens. Despite these advantages, industrial implementation of these techniques has been slowed by the extensive computational resources required to process large-scale time-domain data, particularly in high-speed applications.

This study aims to harness the strengths of Phase-based Motion Processing [3] and Phase-based Video Motion Magnification [4] to rapidly estimate the spectral content of vibrating structures, extract their operational deflection shapes (ODSs) [2], and perform full-field operational modal analysis (OMA). To evaluate these methodologies, two industrial experimental case studies in the aerospace field are presented. The first one involving a full-scale aircraft undergoing Ground Vibration Testing (GVT), and the second one considering a Direct Field Acoustic Testing (DFAT) on the PROBAV satellite. In both studies, the goal is to highlight the potential to analyze the spectral characteristics of structural vibrations and extract critical ODSs.

2. DATA PROCESSING FRAMEWORK

The data processing framework, as illustrated in **Figure 1**, follows a similar pipeline as the one in [3]. It demonstrates the process of extracting operational deflection shapes (ODSs) using phase-based video motion magnification (VMM) and discrete Fourier transform (DFT) techniques. The procedure is as follows:

1. **Input Frames:** The process begins with a sequence of video frames capturing the dynamic behavior of a structure (e.g., a cantilever beam under vibration).
2. **Multi-Scale Decomposition:** Each frame is decomposed into multiple spatial scales using a complex steerable pyramid transform. The leftmost column in the figure represents these spatial scales, ranging from fine to coarse resolution.
3. **Phase Extraction:** For each scale, phase information is extracted from the complex components of the transformed images. The middle column in the figure shows the phase differences, which reveal motion characteristics at each scale.
4. **Spectral Analysis with DFT:** The phase difference images are then processed using the discrete Fourier transform (DFT) to analyze the frequency content of the motion. This step helps in isolating specific vibrational modes.
5. **ODS/Modal Magnification:** During this step, the phase differences obtained in the previous stage are amplified by a magnification factor, denoted as " α " in the figure. This process directly enhances the phase shifts to exaggerate the visible motion in the video. The amplified phase information is then used to reconstruct the image sequence, allowing subtle structural vibrations to be visualized more clearly.
6. **Reconstruction and Visualization:** Finally, the amplified phase information is used to reconstruct an image sequence, allowing for the visualization of the operational deflection shapes (ODSs) of the structure. The rightmost image in the figure shows a colored 3D visualization of the ODS, highlighting the motion magnification at specific frequencies.

This approach provides a robust methodology for non-contact, full-field operational modal analysis (OMA) by leveraging the computational strengths of phase-based motion processing and the spectral precision of DFT.

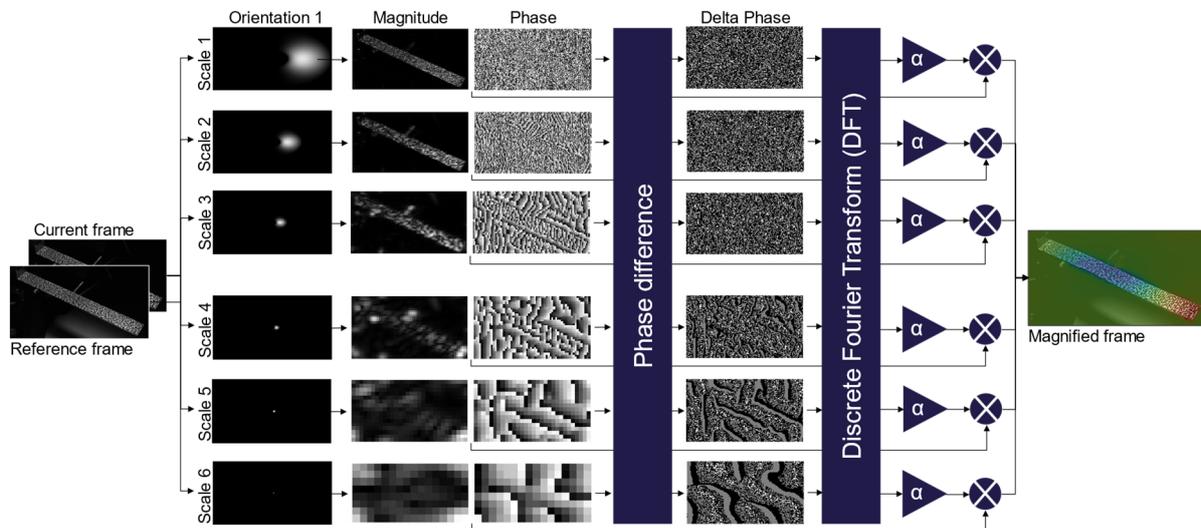


Figure 1. Data Processing Framework.

Extracting full-field operational deflection shapes (ODSs) across the entire frequency spectrum is a highly memory-intensive process due to the overcomplete nature of the data representation. To illustrate the scale of this challenge, consider a video recorded at 1024 frames per second (FPS) with a 4-mega-pixel resolution, using 8-bit color depth, over a 2-second duration. This raw video alone would require approximately 8 GB of storage.

When processed using the Complex Steerable Pyramid (CSP) with the minimal configuration of 4 orientations and octave scales, the data becomes 16/3 overcomplete. Additionally, computational operations involve converting the original 8-bit integer (uint8) data to a 32-bit floating-point (float32) format, further increasing the memory requirements by a factor of 4. Consequently, the memory needed to store the video in the CSP domain could escalate to about 340 GB. By retaining only the phase shift information and discarding the amplitude data at each sub band, this requirement can be reduced by half to roughly 170 GB by storing only the phase shift signals.

To manage this significant computational demand, the ODS extraction process is divided into two main stages. Initially, a global spectral analysis is performed to select specific target frequencies for ODS visualization. This stage can either be accomplished by using accelerometer data or VMM data based on small ROIs across the structure. In the second stage, a sparse selection of full-field spectral components is extracted and utilized to generate the animated ODS, significantly optimizing the memory usage and computational efficiency.

3. EXPERIMENTAL CASE STUDIES

To assess the proposed methodologies and demonstrate their advantages and limitations, two distinct experiments were conducted: a GVT on an F-16 aircraft and a DFAT on a PROBA V satellite.

3.1. F-16 GVT

Figure 2 illustrates the two-step process previously explained for extracting ODSs using a computationally efficient approach that balances global spectral analysis with targeted full-field visualization. The process begins with test preparation and camera setup, as shown on the left side of the figure. The F-16 aircraft is positioned for Ground Vibration Testing (GVT), and the camera is is

strategically placed to capture the dynamic behavior of the whole structure. The cameras used for this measurement campaign are 5 MPx resolution cameras (Blackfly S USB3) running at 50 fps. The structure was excited using a chirp signal with a bandwidth [0-20] Hz. In the measurement phase, a series of frames are captured during the structure excitation.

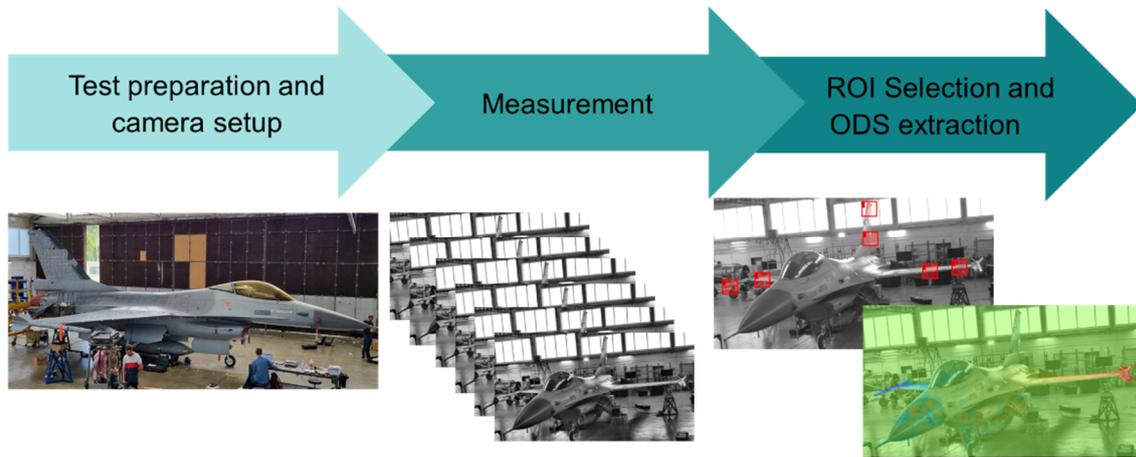


Figure 2. Measurement Campaign Framework.

In the post-processing phase, small ROIs, highlighted by red rectangles in **Figure 3**, are first selected to conduct a full-spectrum analysis that identifies the relevant spectral lines where significant motion occurs.

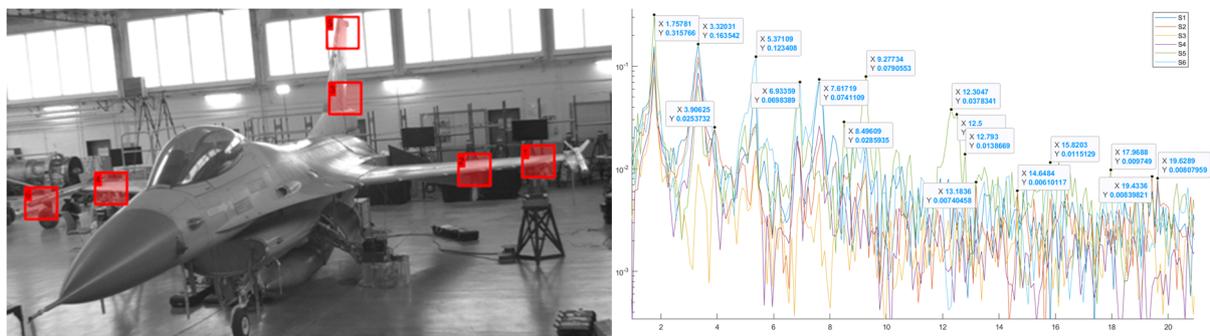


Figure 3. ROIs selection and relative full spectra plot.

In the second step, full field operational deflection shapes are extracted for the selected frequency lines and presented in **Figure 4**. To easily display the animated operational deflection shapes on paper, the magnified images are overlaid with a color map showing the delta phase behavior. The analysis of the ODSs led to the conclusion that the first three peaks are dominated by the rigid modes of the plane, occurring at approximately 1.8 Hz, 3.3 Hz, and 3.9 Hz. The first bending modes of the wings are observed at 5.4 Hz. Additionally, two bending modes related to the missiles are found at 6.9 Hz (with the missiles rotating in opposite phases) and 7.6 Hz (with the missiles in phase). Lastly, the fin mode is identified at 12.3 Hz.

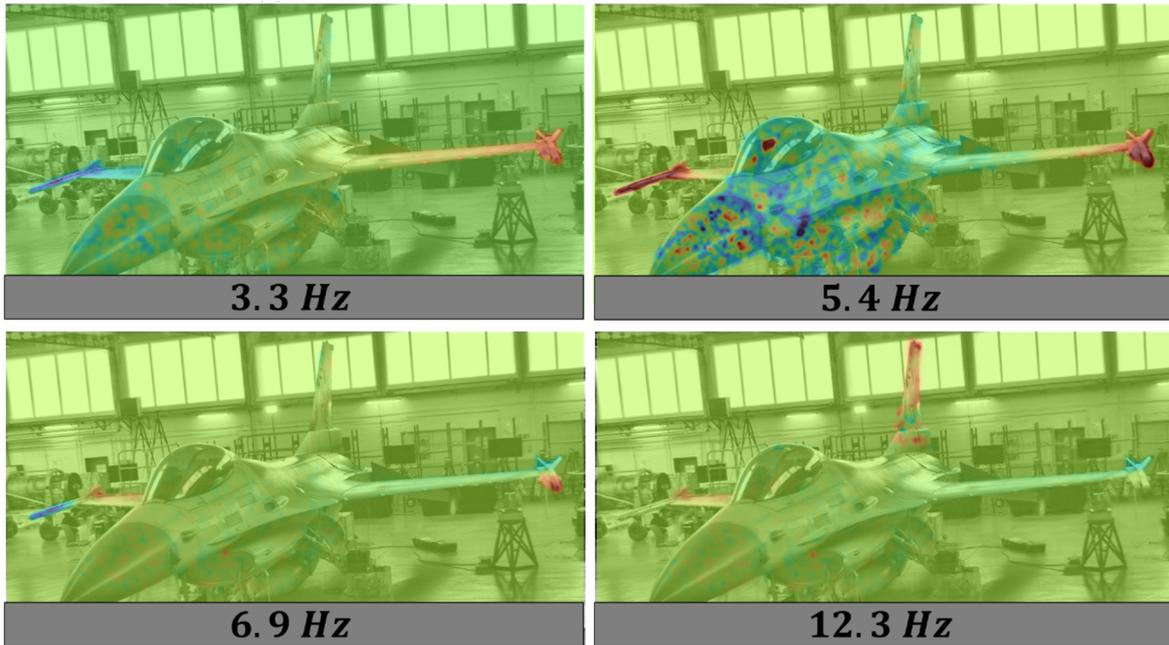


Figure 4. F-16 selected ODSs.

3.2. PROBA V DFAN

The second measurement campaign was conducted on the PROBA V satellite undergoing a DFAT. The processing workflow follows similar steps as the F-16. The cameras used for this measurement campaign are 2 MPx high speed camera (iX Camera 510) running at 1024 fps. The structure was excited using acoustic excitation in the range [2-500] Hz. The only difference with respect to the F-16 relies on a differentiation in the first stage of the two stages approach of the post processing phase, Figure 5.

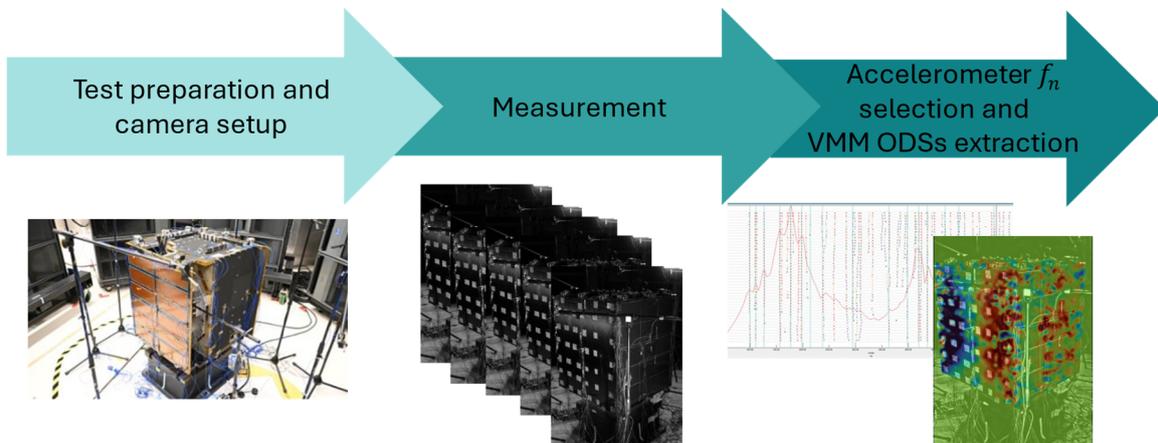


Figure 5. Measurement Campaign Framework.

In this case, multiple accelerometers were installed on the structure to both validate the results from the VMM and to provide input for selecting the spectral lines used in the extraction of ODSs. Figure 6 illustrates the accelerometer stabilization diagram, which was used to select the poles of the structure, further used in the visualization of the critical ODSs.

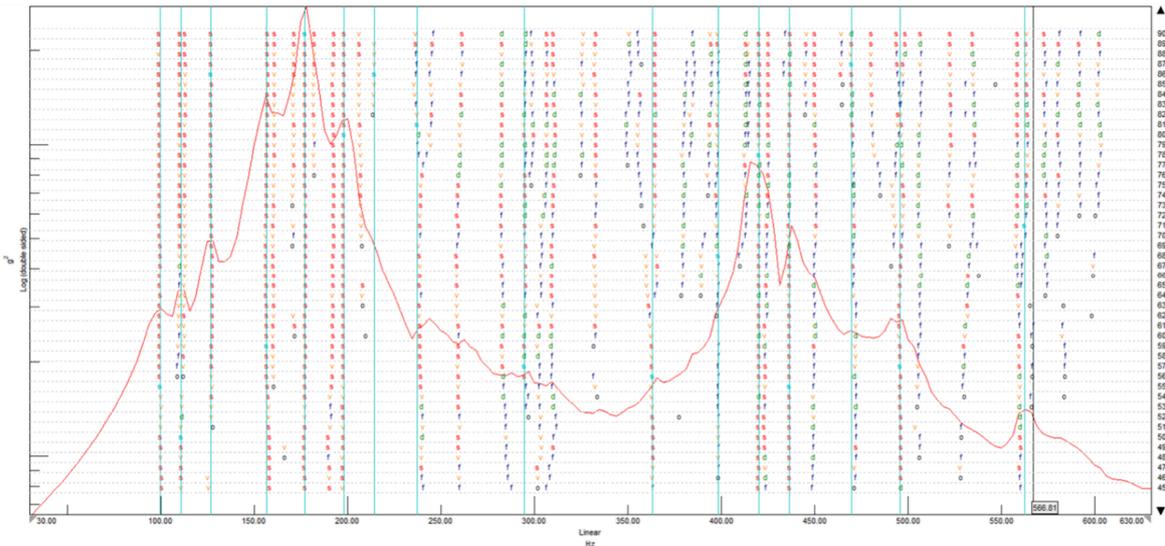


Figure 6. Accelerometers' stabilization diagram.

The selected natural frequencies are used as input to get the plots in **Figure 7**. Just three ODSs are shown, corresponding to the breathing mode at 110.5 Hz, the velocity panel (VP) first bending mode at 125.5 Hz and the VP first torsional mode at 176.3 Hz.

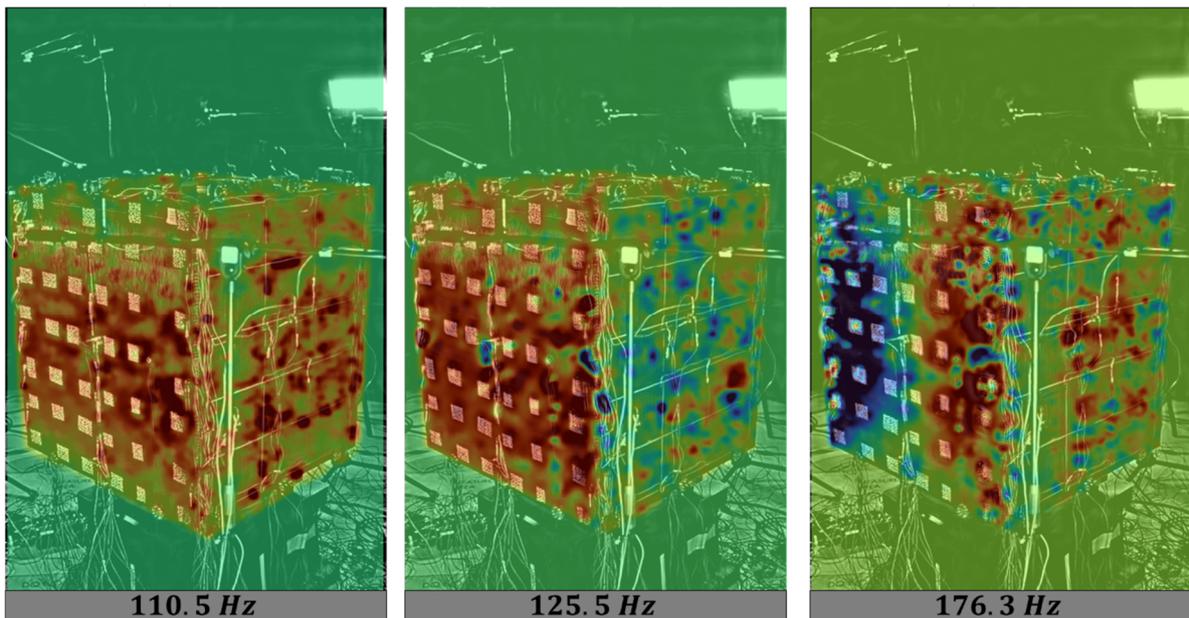


Figure 7. PROBA V selected ODSs.

The obtained mode shapes are then compared to the accelerometer data shown in **Figure 8**. A qualitative comparison indicates that the results from the VMM are consistent with those from the accelerometers, confirming the validity of the extracted full-field ODS.

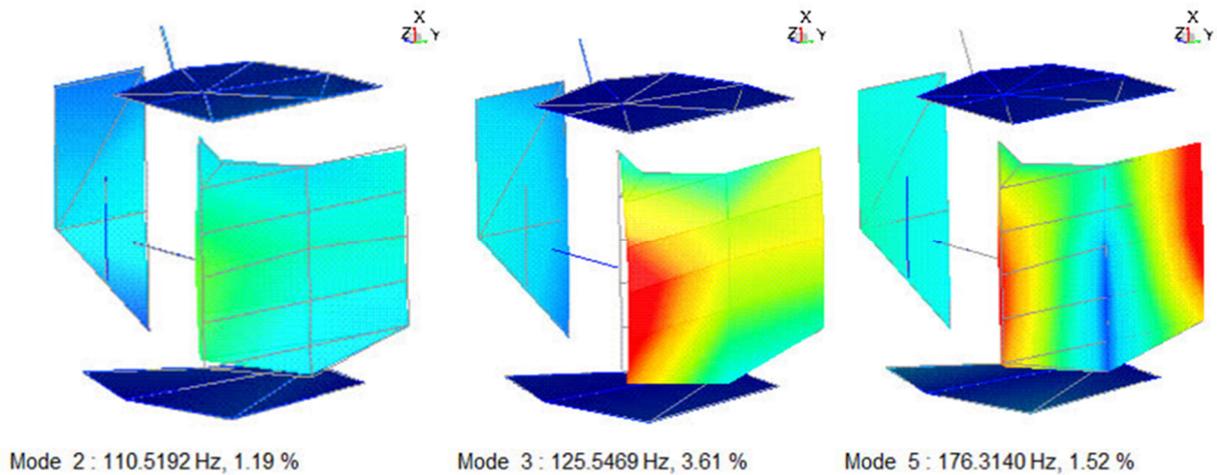


Figure 8. PROBA V accelerometers' mode shapes.

3.3. CONCLUSIONS

This study demonstrated the effectiveness of Video Motion Magnification (VMM) for full-field Operational Deflection Shape (ODS) characterization in structural dynamics. Through the application of phase-based motion processing and discrete Fourier transform (DFT) techniques, the proposed framework enabled non-contact, high-resolution visualization of structural vibrations across diverse industrial contexts. The experimental campaigns on the F-16 aircraft during Ground Vibration Testing (GVT) and the PROBA-V satellite during Direct Field Acoustic Testing (DFAT) highlighted the versatility of VMM in capturing critical vibrational modes. The results validated VMM's capability to accurately replicate traditional accelerometer-based measurements, proving its robustness and reliability. Our test proved the validity of using VMM either as a standalone application, or in synergy with existing technologies.

One key advantage of the proposed methodology is its ability to handle large-scale datasets through a two-stage processing approach. By combining global spectral analysis with targeted full-field ODS extraction, the method effectively reduced computational load and memory requirements. While VMM provides significant benefits, including increased robustness and full-field data acquisition, a few challenges remain in the required data management and computational burden. Future research could explore advanced data compression techniques and parallel processing algorithms to further optimize performance.

Overall, our findings confirm that the combination of VMM with efficient processing strategies is a promising tool for advancing structural dynamics characterization, offering a powerful alternative to traditional measurement techniques.

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REFERENCES

- [1] J. Baqersad, P. Poozesh, C. Niezrecki, and P. Avitabile, "Photogrammetry and optical methods in structural dynamics – A review," *Mech Syst Signal Process*, vol. 86, pp. 17–34, Mar. 2017, doi: 10.1016/j.ymsp.2016.02.011.
- [2] F. Cosco, J. Cuenca, W. Desmet, K. Janssens, and D. Mundo, "Towards phase-based defect detection: A feasibility study in vibrating panels," *J Sound Vib*, vol. 537, Oct. 2022, doi: 10.1016/j.jsv.2022.117196.
- [3] N. Wadhwa, M. Rubinstein, F. Durand, and W. T. Freeman, "Phase-based video motion processing," *ACM Trans Graph*, vol. 32, no. 4, Jul. 2013, doi: 10.1145/2461912.2461966.
- [4] J. G. Chen, N. Wadhwa, Y.-J. J. Cha, F. Durand, W. T. Freeman, and O. Buyukozturk, "Modal identification of simple structures with high-speed video using motion magnification," *J Sound Vib*, vol. 345, pp. 58–71, Jun. 2015, doi: 10.1016/j.jsv.2015.01.024.
- [5] Y. Yang *et al.*, "Blind identification of full-field vibration modes from video measurements with phase-based video motion magnification," *Mech Syst Signal Process*, vol. 85, pp. 567–590, 2017, doi: 10.1016/j.ymsp.2016.08.041.
- [6] P. Guillaume, S. Vanlanduit, H. Van Der Auweraer, B. Peeters, P. Verboven, and S. Vanlanduit, "A poly-reference implementation of the least-squares complex frequency-domain estimator," in *InProceedings of IMAC: A Conference & Exposition on Structural Dynamics, Society for Experimental Mechanics.*, 2003.
- [7] B. Peeters, H. Van der Auweraer, P. Guillaume, and J. Leuridan, "The PolyMAX Frequency-Domain Method: A New Standard for Modal Parameter Estimation?," *Shock and Vibration*, vol. 11, no. 3–4, pp. 395–409, 2004, doi: 10.1155/2004/523692.