High-Frequency Modal Analysis via Low-Speed DIC: Mitigation of Harmonic Peaks in the FRF

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***Abstract*— Digital Image Correlation (DIC) is a technique that has seen a growth in popularity for use in modal analysis, due to its full-field, non-contact measurement capabilities. Recent developments in the field are focused on achieving reliable data acquisition at rates of up to 1 kHz using cost-effective configurations. This study explores the potential of using a low-speed stereo camera configuration to assess the vibrational response of a structure. A previously implemented technique, which reconstructs down-sampled data collected by time-shifting the trigger of a stereo-camera system [1], resulted in the introduction of harmonic peaks in the frequency response function (FRF) of the test specimen. To identify the underlying causes, a detailed analysis was performed using an exclusion-based approach. In contrast to the prior method, a novel technique was developed to collect down-sampled data by temporally displacing the force signal while maintaining a constant camera acquisition frequency. Preliminary results indicate the need for further investigation, and post-processing algorithms were evaluated to mitigate harmonic peaks, of which the Cepstral filter demonstrated successful attenuation.**

Keywords*— Digital Image Correlation; Modal Analysis; Low-speed Camera; Down-sampled Data; Post-processing Algorithms; Cepstral Filter

I. INTRODUCTION AND BACKGROUND

In the digital age, the testing and validation of final designs remains a critical aspect of the product development process. This is particularly true regarding test cycles that must be short, cost-effective, and capable of addressing conflicting performance requirements.

Testing methodologies can be broadly classified into two categories: contact-based sensors, which include devices such as accelerometers and strain gauges, and optical techniques. Contact-based sensors offer a number of advantages, including low computational costs, easy configuration, and suitability for high-frequency data acquisition. However, these sensors only provide measurements at the point of contact and are susceptible to errors introduced by the additional mass or stiffness of the sensors themselves. Furthermore, the unavoidable use of wires for data transmission can introduce electrical noise and complicate the testing of rotating structures, such as wind turbines [2].

In order to address these limitations, optical measurement techniques have been developed over the years [3]. Of these, particular attention has been given to Digital Image Correlation (DIC) due to its capacity to perform accurate, full-field, non-contact measurements. DIC is employed for a variety of purposes, particularly in the investigation of structural systems, subsystems or material samples under static, dynamic, or fatigue loading conditions.

The DIC process involves the capture of a sequence of images of a surface with a speckle pattern applied (Fig. 1). A region of interest (ROI) is divided into an evenly spaced virtual grid by defining subset dimensions, with displacements computed at each grid point to produce a full-field analysis.

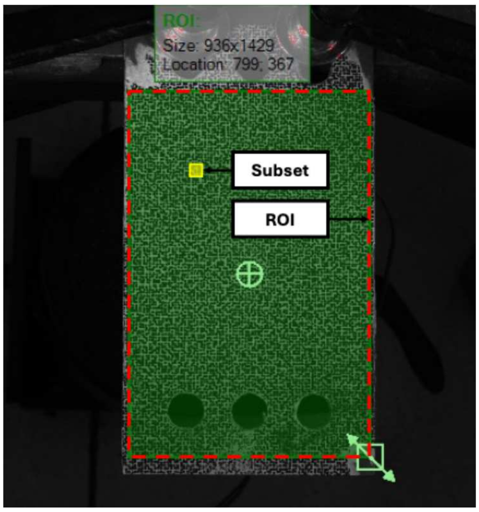

Fig. 1. DIC reference image example

The fundamental computational unit in DIC is the subset (or facet). The algorithm tracks the movement of the subset's centre point, P (x, y), from the reference image (before deformation) to the deformed one, P' (x', y') (Fig. 2). Between different instants, displacements are determined by correlating subsets from two different images based on grey-intensity level [4]. From these displacement fields, strain fields can be derived through smoothing and differentiation [5].

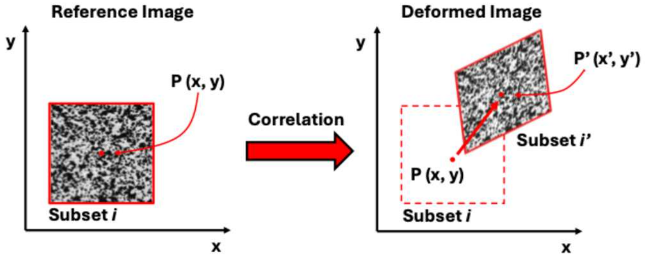

Fig. 2. Schematic of a reference and corresponding target subset after deformation.

The employment of a stereo camera setup enables DIC to evaluate both in-plane and out-of-plane deformations. The latter are more commonly known as 3D DIC or volumetric digital image correlation (VDIC). In the current study, a 3D DIC configuration was utilized, as illustrated in Fig. 3.

Despite the advantages of DIC, the production of large volumes of data is a limitation, as are the camera acquisition frequency and resolution, which constrain its use for applications requiring very high frequencies [6]. To extend the applicability of DIC to high-frequency modal analysis using low-speed cameras, a reconstruction technique for under-sampled signals has been implemented [6, 7]. This approach allows high-resolution imaging at relatively low frame rates, reducing the cost of the test architecture [1]. In this study, two low-speed cameras were employed.

In order to perform modal analysis up to the desired frequency, it is necessary to ensure compliance with the Nyquist-Shannon theorem during the image acquisition and the subsequent signal reconstruction process. The following description outlines the reconstruction process: during a force cycle, a number of images are collected according to the camera acquisition frequency. Subsequently, a sample of the same size is collected during the subsequent force (or acquisition) cycle, with the acquisition sequence shifted by a delay in time equal to the inverse of the desired acquisition frequency. This process is iterated until the target sampling frequency is achieved (Fig. 4).

However, an analysis of the frequency response functions (FRFs) revealed harmonic peaks unrelated to the structure being tested. These peaks were instead due to the data acquisition and processing method [8]. Such peaks are defined as harmonic, given that they recur at a specific frequency. It has been observed that this frequency is equal to the acquisition frequency of the camera system.

As demonstrated in Figure 5, this phenomenon can be illustrated by the results of a test in which the acquisition frequency was set to 25 fps. In this test, harmonic peaks occurred precisely at this frequency's multiples. As indicated by the red arrows, these artefacts were especially notable in the high-frequency domain. Tests using high-speed cameras confirmed the absence of such effects, thereby highlighting the origin of the problem.

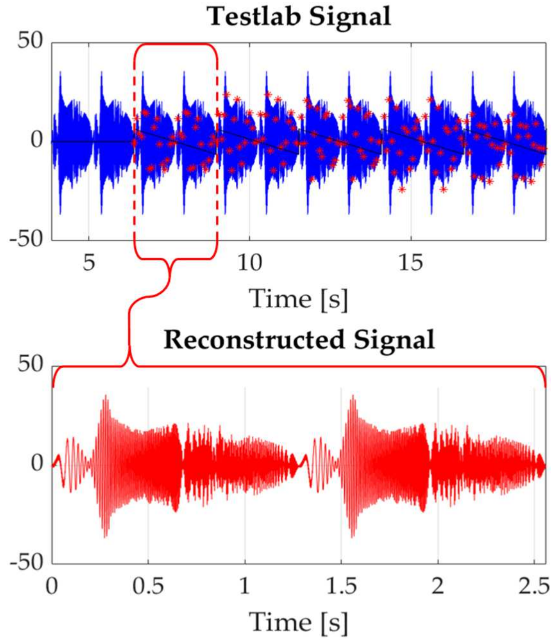

Fig. 4. Reconstruction logic.

The present study investigates the causes of harmonic peaks through a systematic exclusion process. Potential causes under investigation include non-periodicity of the structure (addressed through static testing), poor synchronization between stereo cameras (tested through 2D analysis with a single camera), and resetting of reference images during acquisition for each acquisition cycle. Despite these efforts, the spurious peaks persisted.

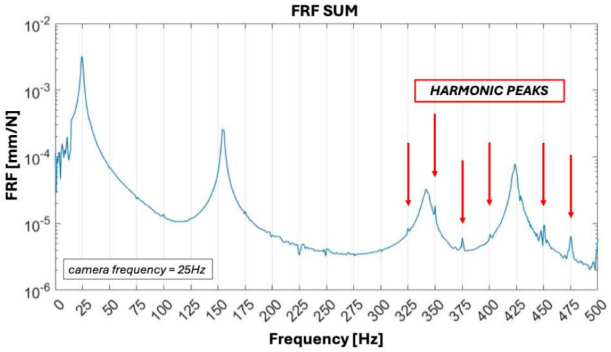

Fig. 5. FRF obtained in DIC test with low-speed camera (25 fps).

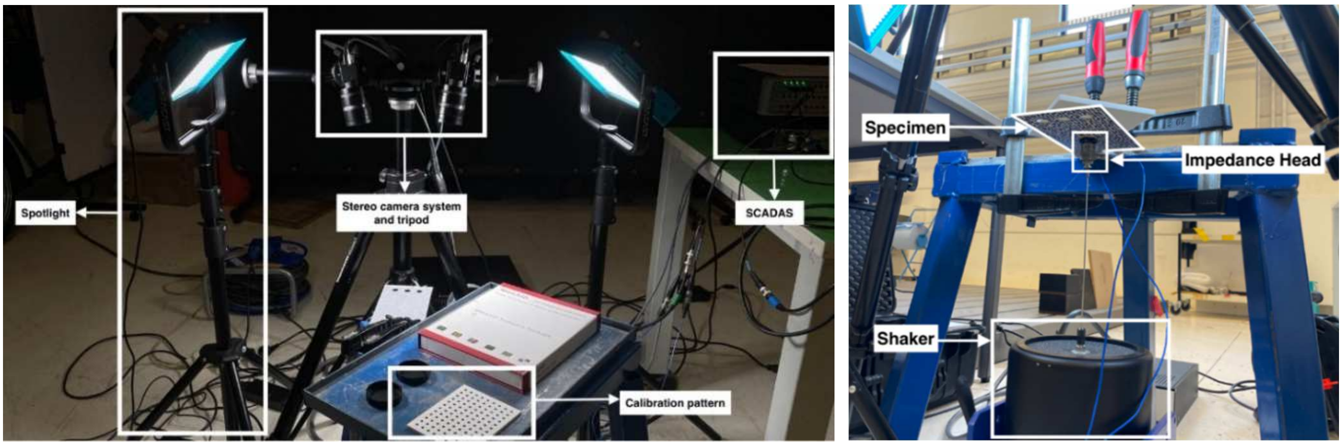

Fig. 3. General setup for DIC analysis: spotlights, stereo camera system and tripod, SCADAS and calibration pattern (on the left); specimen, impedance head and shake (on the right).

In order to address this issue, a novel technique was implemented, whereby the forcing signal was shifted in time rather than the camera acquisition sequence during undersampling. Although this approach shows promise, further investigation is required. Furthermore, an additional method was investigated which captured a single image per force cycle, although this requires further validation. Finally, to produce FRFs suitable for industrial applications, post-processing solutions were evaluated. The generated FRFs were then subjected to filtering using a number of different techniques, including the Cepstral Filter [9], the Vold-Kalman Filter [10], and the Piecewise Detrending Filter [11]. The most favourable outcomes were produced by the Cepstral Filter, effectively attenuating artefacts and isolating the intrinsic resonance peaks of the tested structure.

The structure of this paper is organized in accordance with the progression of the study. Section 2 provides a detailed account of the methods and techniques that were implemented in order to address the problem. Section 3 discusses the post-processing filters that were applied to the data. Finally, Section 4 summarizes the results, and Section 5 outlines future steps.

II. METHODOLOGY: SYSTEMATIC INVESTIGATION OF ERROR SOURCES

In order to ascertain the origin of the harmonic peaks, a systematic investigation was conducted. This investigation entailed the analysis of the error sources related to the algorithm and the experimental setup. Various strategies were implemented in order to isolate each potential source.

A. Non-periodicity of the structure

One area of investigation pertained to the potential for the structure under examination to demonstrate non-periodic behaviour, with the potential to impact the signal reconstruction process. Consequently, a static test was conducted.

The Power Spectral Density (PSD) was utilized as a diagnostic instrument for the analysis. Displacement measurements in the X, Y and Z directions were collected from three arbitrarily selected points on the structure. Despite the static nature of the test, spurious peaks persisted in the PSD, definitively ruling out structural non-periodicity as the source of the problem. The corresponding results for the out-of-plane direction are presented in Fig. 6. However, similar results have been obtained for the in-plane directions.

B. Poor time synchronization between cameras

Following the completion of the test described in Section II.A, it was determined that the discrepancy in the measurements was due to the configuration of the setup (hardware or software) rather than the test sample. Consequently, the possibility of poor synchronization between the two cameras making up the stereo system was further investigated. A two-dimensional static DIC test was therefore carried out.

As before, the PSD of in-plane displacements was calculated from three randomly selected points, as shown in Figure 7. As only one camera was used, out-of-plane displacements could not be assessed. The results indicated that poor synchronisation between the cameras was not the cause of the error, as the harmonic peaks at the camera sampling frequency (12.5 Hz) were still present.

C. Resetting noise from the cameras

In order to evaluate displacements, the DIC software correlates each image with a reference image. This process enables the estimation of a translation vector map representing the displacement time history of the structure. However, it should be noted that errors may be introduced whenever the continuous image acquisition sequence is interrupted and shifted in time in accordance with the reconstruction algorithm.

To address this potential source of error, a modified algorithm was implemented. In this approach, the initial image within each acquisition block was designated as the reference image for that block. The displacements within each block were calculated in relation to the block's designated reference image. Additionally, the displacement of the block's reference image in comparison to the global reference was superimposed onto the block.

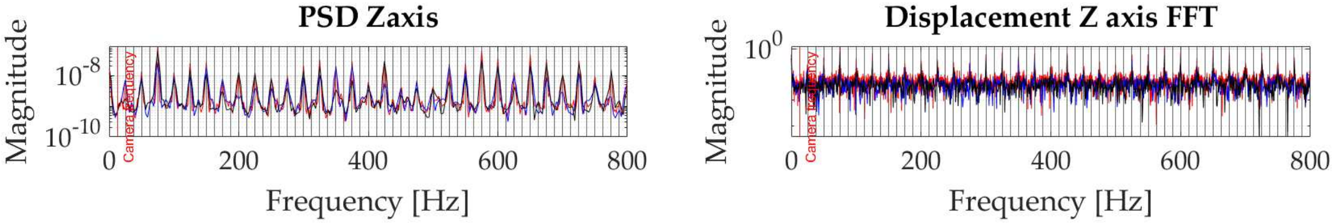

Fig. 6. PSDs (left) and displacements (right) along Z-direction. Camera frequency sets at 12.5 fps and global acquisition frequency at 800Hz. Different colors for three different points randomly located on the structure surface.

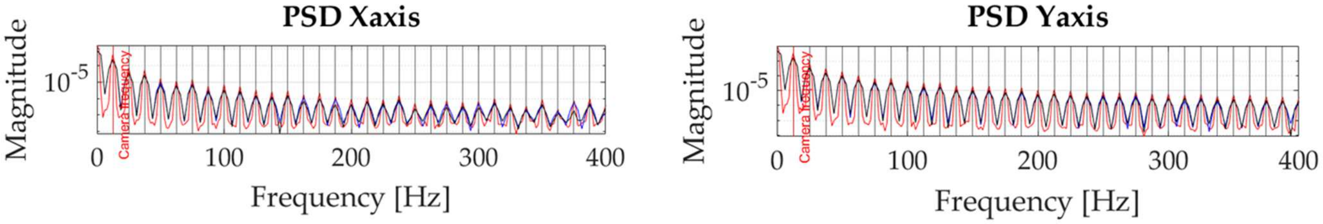

Fig. 7. PSDs along in-plane directions. Camera frequency sets at 12.5 fps and global acquisition frequency at 800Hz. Different line colors for three different points randomly located on the structure surface.

This approach ensured that the displacement continuity was evaluated independently for each acquisition block while maintaining consistency with the test's initial reference image (see Fig. 8 for a visual representation of the underlying logic).

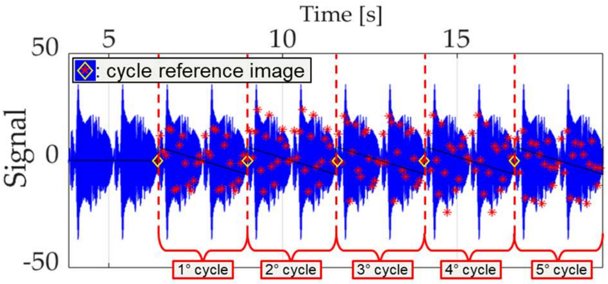

Fig. 8. Reconstruction and analysis logic implemented to rule out resetting noise as source of harmonic peaks.

Nonetheless, harmonic peaks were observed in the resulting power spectra (Fig. 9), indicating that the resetting noise during image acquisition was not the primary source of the error. The corresponding results for the out-of-plane direction are shown; however, similar results have been obtained for the in-plane directions.

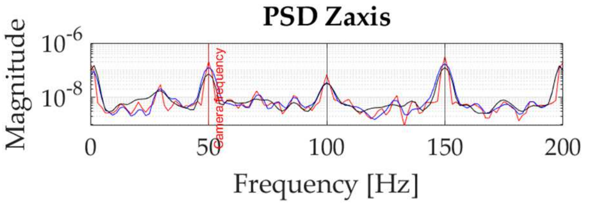

Fig. 9. PSDs along out-of-plane direction evaluated according to the algorithm in Fig. 8. Camera frequency set at 50 fps and global acquisition frequency at 400Hz. Different line colors for three different points.

D. *Force shifting approach*

In order to address the persistent issue of spurious peaks and achieve the goal of implementing high-frequency modal analysis using 3D-DIC with low-speed cameras, a novel methodology was explored. This methodology entailed modifying the excitation signal with the objective of ensuring temporal continuity in the camera acquisition process. To the best of the authors' knowledge, this approach has not been previously reported in the literature and represents the first implementation of such a technique in the context of DIC-based modal analysis.

A strong correlation was observed between the camera acquisition frequency and the error introduced into the FRFs by harmonic peaks. Therefore, the force-shifting method was implemented. According to this new approach, the trigger signal sent to the cameras remains constant at a certain frequency, while the excitation signal is modified.

In the strategies previously described, the duration of the excitation was set to be equal to that of the acquisition block, resulting in the excitation signal being reproduced iteratively until a complete acquisition was achieved. Following each acquisition block, the sequence of pulses transmitted to the cameras was delayed by a duration equivalent to the inverse of the sampling frequency. Conversely, in the force shifting method, the excitation signal's duration is shortened by a time equal to the reciprocal of the test acquisition frequency, thereby enabling signal restructuring according to the desired test sampling frequency. The signal length is set to the length used in previous methods minus the inverse of the sampling acquisition frequency. Concurrently, the camera receives pulses at a constant frequency.

This method was effective in ensuring the temporal continuity of the acquisition process. However, despite representing a novel approach to the problem, the issue of harmonic peaks remained unresolved.

III. POST-PROCESSING

Following an evaluation of the available techniques for addressing the artefacts, it was established that post-processing the acquired signal could result in the generation of an accurate frequency response function, which would be suitable for industrial and scientific contexts. Post-processing entails the application of filters with the objective of eliminating noise or interference from the signal, while ensuring the preservation of its intrinsic characteristics.

The present study set out to identify the most effective filter for mitigating harmonic peaks without compromising the quality of the signal. To this end, three filters were tested: the Cepstral filter [9], the Vold-Kalman filter [10], and the Piecewise Detrending filter [11]. The results are presented in Fig. 10, which shows a comparison of the original and post-processed FRFs for the three filtering techniques.

A. *Cepstral Filter*

The Cepstral filter is based on the mathematical concept of the cepstrum, which is defined as the inverse Fourier transform (IFT) of the logarithm of a signal's spectrum [9]. Mathematically, it can be expressed as follows:

$$C_p = \mathcal{F}^{-1}[log(|\mathcal{F}(f(t))|)] \tag{1}$$

This method is commonly employed to detect periodic structures within frequency spectra [12]. In this study, a low-pass filter was applied to the cepstrum of the displacement signal along the three spatial directions. The corrected displacement signal was then reconstructed in the time domain. This technique effectively removes harmonic components, albeit with some impact on signal amplitude (Fig. 10).

B. *Vold-Kalman Filter*

The Vold-Kalman (VK) filter is a variant of the Kalman filter that has been optimised for systems with noisy measurements. It employs a smoothing algorithm to predict the state of a system while minimising noise interference by iteratively comparing predicted and actual measurements [10].

The Vold-Kalman filter demonstrates its primary strength by balancing the minimization of noise and the preservation of signal fidelity. Nonetheless, a detailed analysis indicates that the filter appears to intensify, rather than alleviate, the spurious peaks (Fig. 10).

C. *Piecewise Detrending Filter*

The Piecewise Detrending filter is a technical procedure that has been developed for the purpose of extracting trends and fluctuations from time-series data. The operation of this filter can be summarised as follows: the time series is divided into segments, a polynomial is fitted to each segment, and then the polynomial is subtracted to obtain a detrended signal [11]. The order of the polynomial can be adjusted based on the complexity of the trend, with higher-order polynomials capable of capturing more intricate variations. The final step in the process is to obtain the filtered time series by concatenating the detrended segments [11].

Despite the filter's demonstrated efficacy in reducing harmonic components, its implementation inadvertently introduced negative peaks (Fig. 10), thus rendering the FRFs unusable.

IV. CONCLUSIONS

Despite the advances in simulation software that have made the design phase increasingly efficient, physical testing remains an essential component of validating the structural behaviour of a system. Digital Image Correlation offers a robust, non-contact method for performing modal analysis, providing full-field measurements. However, the constraints imposed by the limited acquisition frequency of low-speed cameras and the low resolution of high-speed cameras at high working frequency present challenges for high-frequency applications. In order to address these challenges and reduce the setup cost, this study has explored an under-sampling and signal reconstruction approach combined with various post-processing strategies.

The FRFs that were computed revealed harmonic peaks that were superimposed on the actual FRF. These peaks could be attributed to the methodology of data acquisition and reconstruction rather than to the structure itself. In order to identify the source of these artefacts, several investigative steps were taken. These included the implementation of alternative reconstruction and analysis logic, as well as the conducting of static tests with a stereo and mono camera set-up. Furthermore, alternative data acquisition strategies were explored, such as time-shifting the force signal. Although this method was promising, it did not solve the issue in the analysis output. Despite these efforts, the harmonic peaks persisted.

The application of the Cepstral filter during the post-processing stage yielded optimal outcomes, effectively eliminating artefacts and distortions. However, this filtering technique concurrently led to a discernible diminution in the FRF amplitude, thereby underscoring the dilemma between harmonic suppression and signal amplitude preservation. Although this approach offers a provisional resolution to the issue, it remains a transient solution until the underlying cause of the problem is identified and addressed.

This study demonstrates the feasibility of utilizing low-speed cameras for DIC-based modal analysis when combined with effective signal processing. It highlights the potential and limitations of the method for industrial and scientific applications.

V. NEXT STEPS

This research has provided a solid foundation for the utilisation of low-speed DIC setups in experimental modal analysis, thereby demonstrating their reliability in capturing very fast dynamic structural behaviour. To build on these findings, several key areas for future investigation have been identified:

1) Integration of Strobe Lighting for Synchronization The employment of strobe lighting, synchronized with the camera shutter, has the potential to further enhance time synchronization. By governing the flash intervals with greater precision than the camera exposure, this technique could augment the accuracy of data time synchronization, mitigate harmonic distortions, and broaden the method's applicability to higher frequencies.

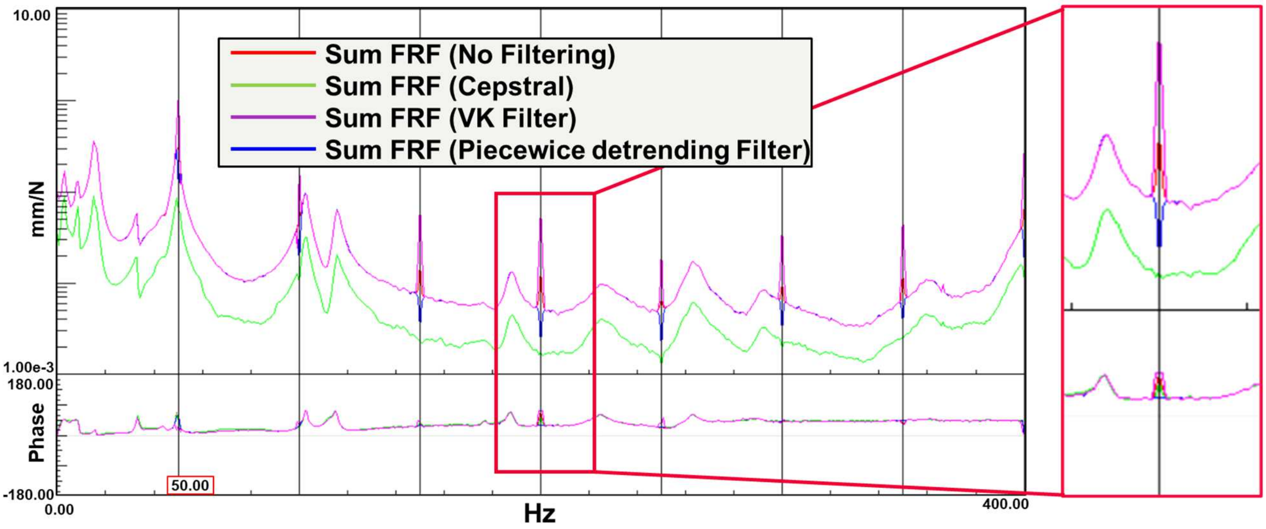

Fig. 10: Comparison of FRF obtained after post-process filtering through Cepstral, Vold-Kalman (VK), and Piecewise Detrending Filter.

2) *Sensitivity Analysis of Setup Parameters*

A systematic sensitivity analysis of the experimental setup, incorporating parameters such as camera settings, relative angles, and lighting conditions, has the potential to enhance the signal-to-noise ratio. This analysis may result in the reduction of harmonic peak amplitude, the mitigation of noise, and the expansion of the feasible bandwidth for FRFs.

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