

Image-based vibration analysis: precision and limitations compared to classical methods

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Abstract

Image-based vibration analysis using optical flow is based on high-speed camera recordings that track the motion of surface points between successive frames. This enables full-field, high-resolution measurements of vibrations and deformations. Compared to conventional methods such as Laser Doppler Vibrometry (LDV) and accelerometers, optical flow offers a flexible and efficient alternative for time-synchronous measurements. This study investigates the capabilities and limitations of the method by comparing it with established techniques. Particular attention is paid to the influence of surface reflections, camera motion, illumination changes, and image resolution. The experimental workflow includes validation under ideal conditions, a systematic analysis of disturbance factors, investigations of complex structures, and application to a real-world case. The results are compared with simulation data and LDV measurements to evaluate the accuracy and applicability. The findings provide a solid basis for research and development.

1 Introduction

Image-based vibration analysis using optical flow offers a promising alternative or supplement to classical measurement methods. The aim of this study is to determine the limits of this approach, with a specific focus on modal analysis, and to compare it with established methods. In doing so, various factors that can influence the accuracy of the measurements are considered.

The experimental setup comprises several stages: beginning with a calibration reference measurement, the method is validated under optimal conditions. This includes frequency and amplitude calibration experiments to ensure the accuracy of the image-based measurements. Subsequently, an image-based damping estimation approach is introduced and evaluated, followed by a validation of the damping ratio using synthetic video data generated with the open-source 3D modelling software Blender. Potential sources of error, such as reflections, camera movements, or changes in lighting, are then systematically identified and analyzed.

Furthermore, a real-world structure of moderate complexity is examined to evaluate the performance of the optical flow method under realistic conditions. Finally, a comparison is performed with simulation results as well as measurements obtained from accelerometers and a LDV to further characterize the accuracy and applicability of the method.

2 Image-based vibration analysis

Image-based vibration analysis captures structural vibrations from video recordings. The motion is extracted by software analyzing optical flow [1], a method that detects minute changes in brightness between

consecutive frames. This approach yields high subpixel accuracy, enabling the measurement of displacements well below the pixel size.

The method requires a standalone camera or smartphone with a suitable lens, stable lighting (possibly with a contrast pattern on the surface), and analysis software on a PC. The achievable spatial resolution is directly determined by the camera resolution and the imaging scale (pixel size in the measurement area). The temporal resolution is determined by the frame rate of the camera, which allows analysis of frequencies up to several Kilohertz with currently available high-speed cameras.

The typical procedure for image-based vibration analysis is as follows:

1. Recording of an image sequence during excitation of the structure
2. Calculation of the motion fields (optical flow) between the individual frames
3. Extraction of temporal signals (velocity) at arbitrary image points
4. Analysis in the frequency domain (e.g. operational vibration modes, modal analysis) or in the time domain (e.g. operational vibration modes, velocity-time data)

To convert the pixel movements obtained from the optical flow into real-world units (e.g. m or m/s), scaling using known dimensions in the image is required.

Movements parallel to the viewing-axis of the camera (out-of-plane) cannot be measured directly with a single camera. However, by intentionally tilting the camera, components of the out-of-plane motion can also be captured in the image projection. For a complete and amplitude-accurate measurement of the out-of-plane components, the use of two cameras (stereo) or the consideration of an absolute depth image is required.

3 Image-based damping estimation

Estimating damping ratios involves specific challenges caused by the finite duration of signal, limited frame rates, measurement noise and the resulting discrete frequency resolution. These aspects directly influence the stability and accuracy of frequency-domain damping estimation methods and must be carefully considered when transferring classical vibration analysis techniques to video-based data.

For lightly damped systems, the vibration energy in the frequency range is strongly concentrated around the resonance frequency. Due to the finite observation time and the discrete frequency bins of the Fast Fourier Transform (FFT), the resonance peak may be represented by only a limited number of spectral lines. This can complicate the reliable determination of resonance bandwidths, which are essential for frequency-domain damping estimation approaches.

In this work, dense velocity fields are extracted from image sequences using optical flow and converted into temporal vibration signals. These signals are transformed into the frequency domain using FFT, where they are further modally decoupled using Singular Value Decomposition (SVD). From the isolated modal component at the selected frequency, a synthetic frequency response function (FRF) is generated. The damping ratio is estimated using the half-power bandwidth (-3 dB) method, in which damping is derived from the relationship between the resonance frequency and the bandwidth of the amplitude spectrum. To address the limitations imposed by discrete FFT bins, the -3 dB points are determined from an interpolated spectrum, allowing a more accurate estimation of narrow resonance bandwidths typical for lightly damped structures. In addition, a Lorentzian curve fitting (see Figure 1) approach is applied to the resonance peaks in the frequency domain. This enables a continuous representation of the spectral peak and allows accurate damping estimation even in the presence of limited frequency resolution. The Lorentzian model is particularly well suited for lightly damped systems, as their frequency response around resonance follows a characteristic peak shape that can be well approximated by this function. Furthermore, the fitting process

reduces the influence of noise and discretization effects, leading to more robust and stable damping estimates.

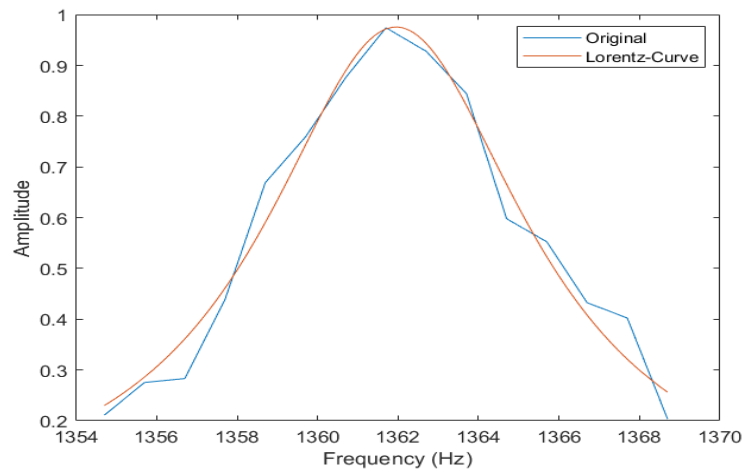


Figure 1: Peak around a resonance. **Blue:** Optical flow signal. **Red:** Corresponding Lorentzian fit used for damping estimation.

A key advantage of image-based vibration analysis is the high spatial resolution provided by optical flow, yielding a large number of spatially distributed vibration signals across the structure. This spatial redundancy supports a robust frequency-domain analysis by enabling consistent identification of spectral characteristics and reducing the influence of local measurement noise. The suitability and performance of the proposed approach are evaluated in the following sections using synthetic and experimental data.

4 Calibration measurement

To evaluate the precision of the frequencies and amplitudes extracted from the optical flow, experimental validations were conducted under controlled conditions. A VCS 401 vibration control system from Spektra, capable of generating defined sinusoidal vibrations, was used for the calibration measurements.



Figure 2: Measurement setup for calibration

A hexagonal prism with a threaded connection to the oscillation unit was used as the test specimen. The test recordings were performed using a perpendicular measurement (exclusively in-plane measurement) with virtually no light reflections and no camera movement. To minimize disruptive vibrations, the high-speed camera was mounted on a wooden tripod, which reduced unwanted influences on the measurement due to its damping properties (see Figure 2, left).

For each measurement, a sinusoidal vibration with a defined frequency of 100 Hz and constant amplitude of 0.1 mm was set on the vibration exciter system. After stabilization, 1,000 images were captured. The built-in accelerometer of the vibration exciter served as a reference signal to evaluate the accuracy of the optical vibration analysis. The results were very promising, particularly at the optimally selected sensor points, which were determined using a method for identifying significant pixels (see Figure 3).

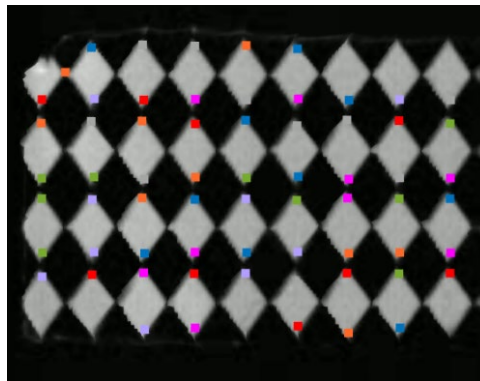


Figure 3: Optimally selected image points (63) are marked in color on the image.

This method is based on selecting pixels with significant brightness differences in their surroundings, which are particularly well-suited for motion tracking. All of these pixels were able to precisely detect the set frequency of the shaker (see Figure 4). Furthermore, the median of all the best measurement points exactly matched the set amplitude of the shaker (see Figure 5 that shows a statistical representation of the amplitude values of all optimal measurement points).

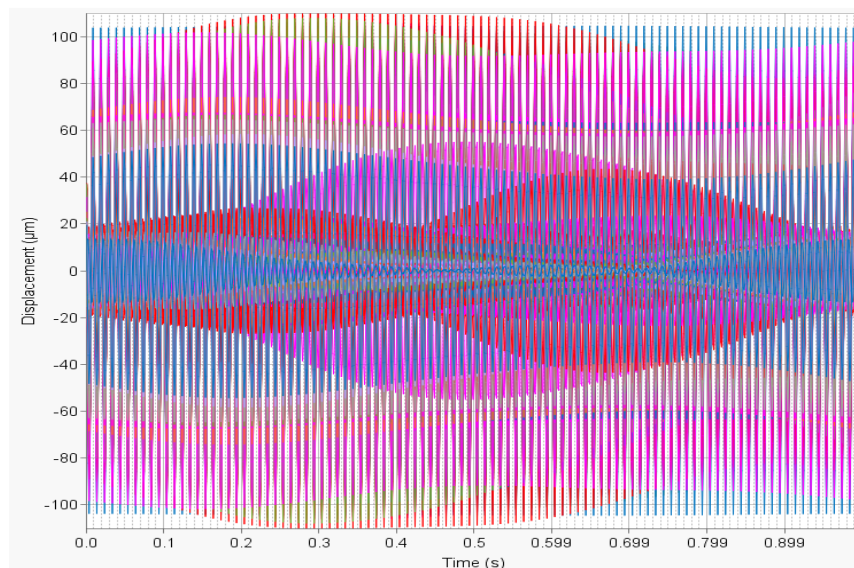


Figure 4: Sine wave excitation at 100 Hz and 0.1 mm amplitude (63 optical measurement points), bandpass filtered at 100 Hz

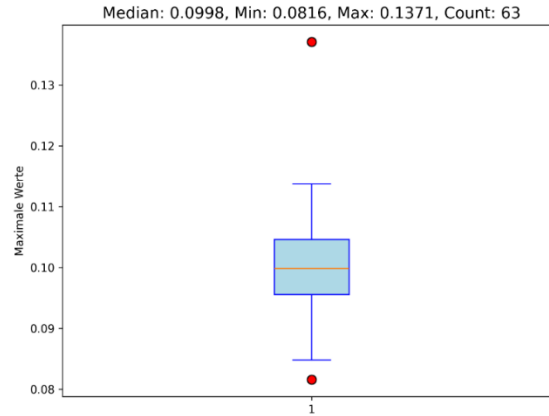


Figure 5: Sine wave at 100 Hz with 0.1 mm amplitude (63 optical measurement points)

5 Validation damping ratio using synthetic video data from Blender

To quantitatively validate the outlined image-based damping estimation approach under fully controlled conditions, a synthetic benchmark dataset was generated. Synthetic video data allow precise prescription of vibration parameters and thus provide ground-truth reference values that cannot be realized in conventional experimental setups. In particular, while shaker-based experiments enable controlled excitation in terms of frequency and amplitude, the damping ratio is an inherent system property and cannot be explicitly prescribed. As a result, generating reference measurements with known damping values is not feasible using classical sensor-based experiments.

5.1 Synthetic data generation

A structural model of the investigated component was first simulated to determine its modal properties, including eigenfrequencies and corresponding mode shapes. Based on these modal characteristics, a physically consistent vibration scenario was constructed in Blender [2], where the structure was animated according to a prescribed single-mode response.

The animation was generated at selected eigenfrequencies of 25 Hz and 100 Hz. For each frequency, synthetic video sequences were created with damping ratios ranging from 0.1 % to 10 % and a defined initial displacement amplitude. The temporal displacement of each surface point followed a damped harmonic motion described by

$$\delta_s(t) = A_0 e^{-\zeta 2\pi f t} \sin(2\pi f \sqrt{1 - \zeta^2} t) \quad (1)$$

where A_0 denotes the initial displacement amplitude, f the eigenfrequency, and ζ the damping ratio. This formulation is consistent with classical single-degree-of-freedom vibration theory and allows precise and reproducible control of the decay behavior. As a result, the generated video sequences contain vibration signals with exactly known ground-truth parameters (see Figure 6).

5.2 Optical-flow-based evaluation

The synthetic video data were processed using the same optical-flow-based evaluation pipeline applied to the experimental measurements. Dense velocity fields were extracted from the image sequences, and local vibration time histories were obtained at numerous spatial locations across the structure. This high spatial redundancy enables a robust frequency-domain analysis, as characteristic spectral features can be consistently identified across multiple measurement points.

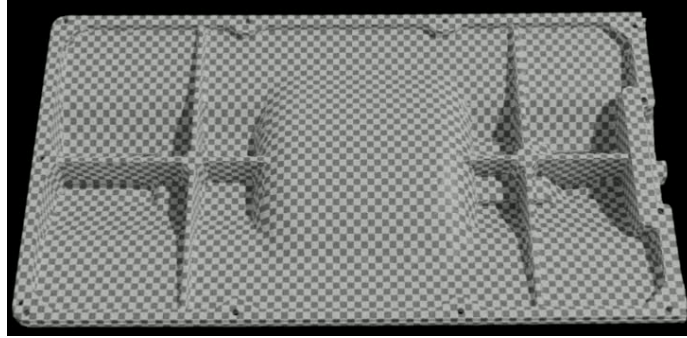


Figure 6: Blender-generated synthetic video with a predefined resonance and adjustable damping ratio, serving as a controlled reference for the WaveCam measurement.

5.3 Validation results

Image-based analysis demonstrates that, for both excitation frequencies of 25 Hz and 100 Hz, the damping ratios estimated from the image-based evaluation show excellent agreement with the ground-truth values prescribed in Blender. Across the complete investigated range from 0.1 % to 10 % damping, the estimated values were virtually identical to the reference parameters, provided that a sufficiently long-time duration was selected for the synthetic video sequences.

The results clearly highlight the fundamental role of the total observation time for frequency-domain damping estimation. For lightly damped cases, the resonance peak is strongly concentrated around the eigenfrequency and is represented by only a few discrete frequency lines especially for short measurement durations. Under these conditions, the -3 dB bandwidth cannot be determined with sufficient numerical stability. Increasing the sequence length improves the frequency resolution of the FFT, enabling reliable interpolation of the half-power points and accurate estimation of the damping ratio.

This behavior is fully consistent with classical sensor-based vibration measurements, such as accelerometer or LDV data, where accurate estimation of low damping ratios likewise requires sufficiently long measurement durations to resolve narrow spectral peaks. The synthetic video experiments therefore confirm that the highlighted image-based damping estimation approach follows the same fundamental signal-theoretic constraints as established vibration measurement techniques and does not introduce additional systematic bias.

5.4 Discussion

Unlike vibration amplitudes, which strongly depend on the projection of structural motion onto the image plane and are therefore sensitive to vibration direction and camera perspective, the damping ratio represents a relative, dimensionless system parameter. Both time- and frequency-domain damping estimators are based on ratios rather than absolute velocity values, making them largely invariant to scaling effects caused by perspective projection. Consequently, the damping ratio is significantly less affected by camera viewpoint and vibration direction than amplitude-based quantities, making it particularly well suited for image-based vibration analysis.

It should be noted that, in this initial validation stage, camera noise and illumination effects were intentionally excluded in order to isolate the fundamental performance of the proposed method. The influence of realistic imaging conditions, including sensor noise and lighting variations, will be addressed in subsequent experimental validations.

Overall, the synthetic video validation demonstrates that optical-flow-based vibration measurements are capable of recovering damping ratios with accuracy comparable to that of classical sensor-based approaches when appropriate acquisition parameters, particularly sufficient time duration, are employed. This provides a robust foundation for the subsequent validation using real experimental data.

6 Disturbances

A key difference between image-based vibration analysis and, for example, classical 1D LDV lies in the respective measurement principle. While – for perpendicular measurements – the LDV detects out-of-plane vibrations, the camera measures in-plane using the optical flow method. This difference in measurement direction can lead to systematic deviations, particularly when the measured movements cannot be clearly assigned to a certain direction. Additionally, various disturbance factors [3] influence measurement accuracy:

- Light reflections: varying reflections on the surface of the test specimen can distort the image pixels and lead to misinterpretations of the movements.
- Camera motion: even the slightest vibrations or movements of the camera can influence the measurement and lead to inaccuracies.
- Quality of image features: The accuracy of optical flow measurements depends heavily on the quality of the image features used. Pixels with low contrast or blurred edges are less reliable and can lead to errors in motion detection. To improve the quality of image features, foiling, the use of individual 3D markers, or the application of textured sprays on the surface of the test specimen can be employed. These methods increase contrast and improve motion detection. Compared to other image-based algorithms, the type of pattern plays a less critical role in the performance of the optical flow, as the algorithm handles different textures well, including those naturally occurring.
- Too low sampling rate or frame rate: As with conventional sensors, the frame rate for image-based vibration analysis should be at least twice (preferably 2.5 times) as high as the highest frequency of the measured vibration to enable accurate motion detection. A sampling rate that is too low can lead to aliasing effects and inaccuracies.

Some of the listed sources of error, such as the sensor's own motion, aliasing effects, or undersampling, as well as reflection and projection effects, generally apply to optical measurement sensors, including, for example, the LDV.

7 Comparison with simulation and conventional measurement methods

7.1 Measurement object, FE model, and test planning

Figure 7 shows a cover plate of moderate complexity, which will be examined below to illustrate the fundamental phenomena using a real-world example. For this cover plate, an FE model with volume elements was first created (see Figure 8), which, under free boundary conditions (“free/free”), yields five elastic eigenmodes up to 2 kHz (Table 1 shows the corresponding natural frequencies).

The FE model was then used for test planning, utilizing ICS's proprietary ICS.sysval software. In particular, a reduced test model with 25 measurement points was derived (see Figure 9), which represents the natural modes up to 2 kHz with sufficient spatial accuracy, provided that measurements are taken only perpendicular to the cover plate (out-of-plane).

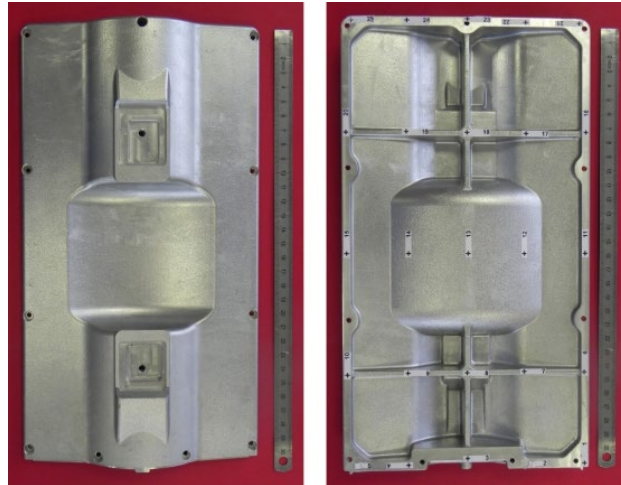


Figure 7: Cover plate (≈ 860 g, $\approx 305 \times 165 \times 33$ mm)

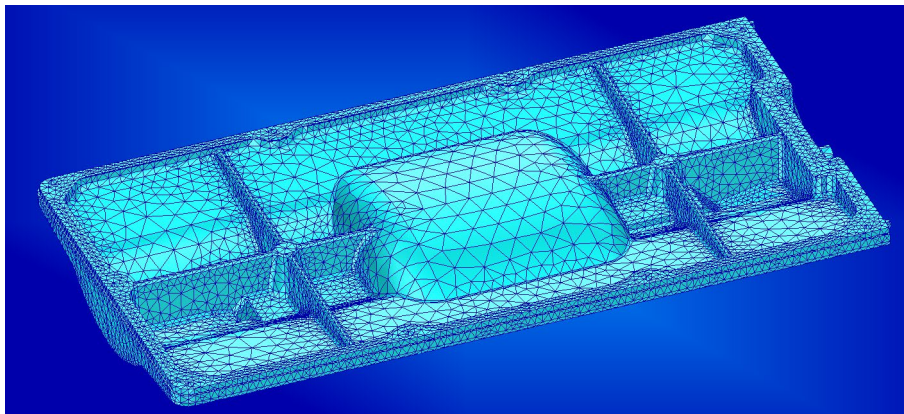


Figure 8: Overview of the FE model

Table 1: FEA natural frequencies from the analytical modal analysis up to 2 kHz

No.	FEA in Hz
1	458.4
2	573.6
3	1074.2
4	1374.0
5	1787.6

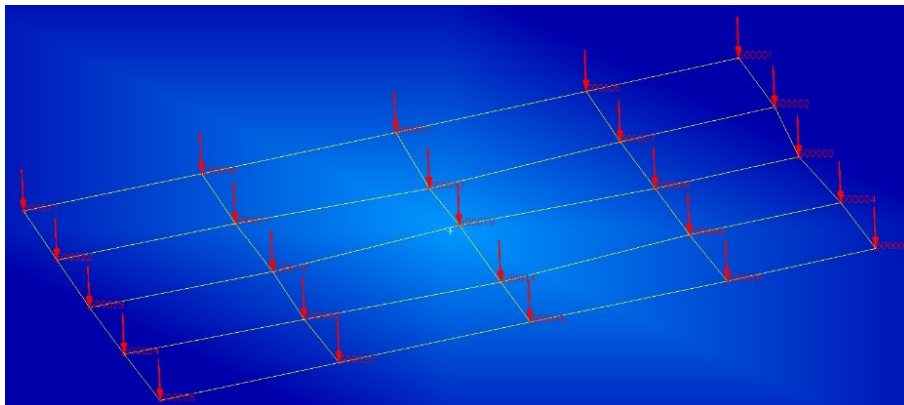


Figure 9: Test model with 25 degrees of freedom perpendicular to the cover plate

7.2 Reference measurements

As reference measurements, a classical acceleration measurement with a moving, manual hammer excitation (see Figure 10) as well as a LDV measurement using a 1D laser scanner and automatic mini-hammer excitation were performed (see Figure 11). The hammer measurement was chosen to avoid detuning of the test object, e.g., due to the connection of a shaker system (see [4] for details).

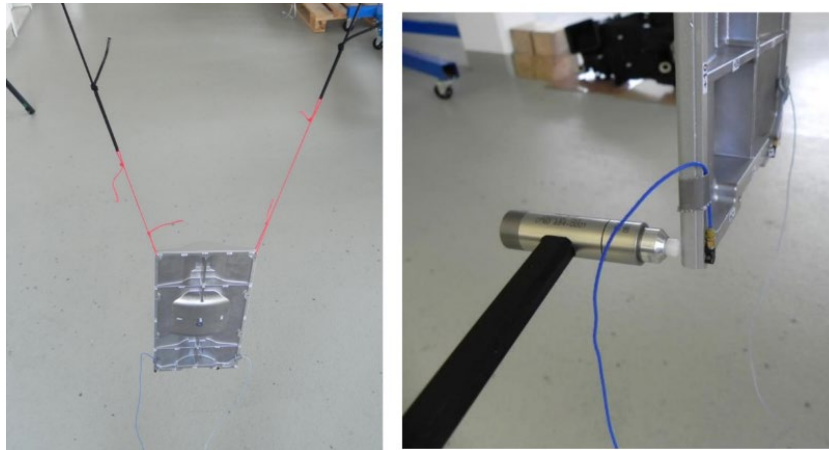


Figure 10: Measurement setup with accelerometers and hammer excitation



Figure 11: Measurement setup with 1D laser scanner and automatic hammer excitation

The measurement with a moving hammer represents a simple standard measurement with relatively low spatial resolution, which provides the essential dynamic characteristics – e.g., for subsequent model validation – at a manageable cost and time investment.

LDV measurement is significantly more time- and cost-intensive – however, it provides a very high spatial resolution of the test object in a reliable and largely automatable manner, provided that such a requirement exists. The results of the experimental modal analyses are shown for both measurements in Table 2 (natural frequencies only) and for the LDV measurement in Figure 12 (modes). As expected, there are practically no differences.

Table 2: Experimental modal data from the reference measurements

No.	FEA in Hz	EMA Acc. in Hz	EMA Laser in Hz
1	458.4	453.4	453.4
2	573.6	567.9	568.6
3	1074.2	1081.1	1081.5
4	1374.0	1364.3	1363.6
5	1787.6	1770.0	1769.1

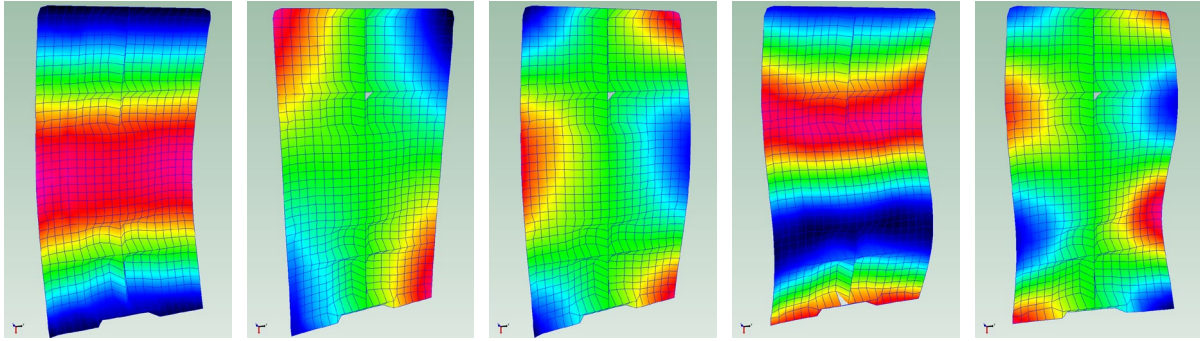


Figure 12: Natural frequencies of the laser measurement at 453.4/568.6/1081.5/1363.6/1769.1 Hz

7.3 Measurement setup with high-speed camera

For the experimental investigations, a Mikrotron EoSens high-speed camera was used, and the WaveCam software from gfai tech was employed to analyze the videos and capture the vibrational movements of the component. The camera was operated at a frame rate of 4527 frames per second (fps) with a recording time of 0.33 s, corresponding to a frequency resolution of 3.03 Hz. The resolution was 500 x 1008 pixels.

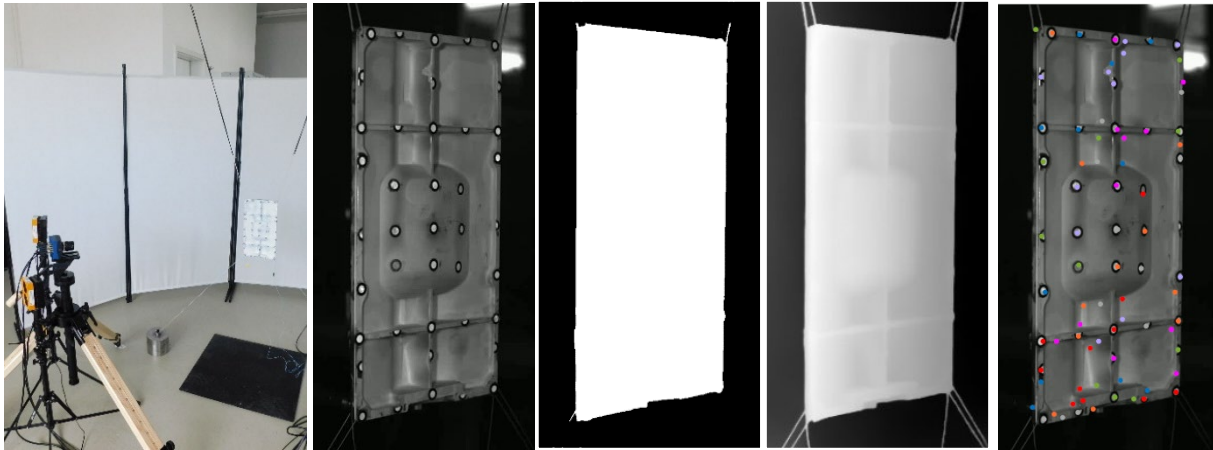


Figure 13: Measurement setup, image, mask, depth image, best sensor points

To improve optical flow quality, the surface of the test object was treated with a matte white spray and marked with 3D markers at selected measurement points. The 3D markers were applied, among other places, to points corresponding to the test geometry as shown in Figure 9. Excitation was performed manually using a modal hammer, analogous to the reference measurement with accelerometers (see also Figure 10 above on the right). Excitation with a mini-automatic hammer was insufficient here, as the achievable response amplitudes were below the level detectable by image-based analysis. Furthermore, compared to the other methods, only a single excitation is required.

The setup (see Figure 13) also enabled the generation of a depth image, which could be used for spatial filtering. As a result, only pixels associated with the component surface were considered, while the surrounding area was excluded from the analysis. Disturbances arose from the bungee cords used for free/free suspension, as these also move in the video. Since the optical flow calculation includes neighboring pixels, these strong movements lead to deviations at nearby measurement points at the edge of the component.

7.4 Pixel-by-pixel depth normalization (perspective correction)

To experimentally capture the vibrations, the optical flow (u , v) was determined. The images were captured at an angle of approximately 45° , so that contributions from all three spatial directions (x , y , z) are present in the image signal; the dominant motion is out-of-plane (z), but due to the projection geometry, this appears only proportionally. To compensate the perspective, a pixel-by-pixel z -compensation is performed based on a depth image $Z(x, y)$ reconstructed by a neural network. Specifically, the flow components are depth-weighted: $u^*(x, y) = Z(x, y) u(x, y)$, $v^*(x, y) = Z(x, y) v(x, y)$, thereby locally canceling the perspective attenuation of the in-plane components as well as the outward-directed flow component resulting from z -movements (optical expansion). The focal length is not explicitly taken into account, as it is approximately constant for all pixels and would act only as a global scaling factor in the subsequent modal analysis; the analysis focuses on relative eigenmodes, not on absolute amplitudes. The modal response functions are derived from the corrected fields (u^* , v^*) (small-angle linearization, perspective projection) and compared with the numerical simulations, which contain exclusively z -vibrations.

7.5 Operational Modal Analysis

The experimental eigenmodes were determined from the corrected optical flow data using operational modal analysis (OMA). For this purpose, the Complex Mode Indicator Function (CMIF) algorithm [5] was employed, which enables robust identification of the eigenmodes even when multiple vibrations are excited simultaneously and reduces the influence of measurement noise. Figure 14 shows the first indicator function of the CMIF algorithm: The best sensor points are marked in red, while the average of the entire pixel region is displayed in black (resonances at 452.7 Hz, 567.4 Hz, 1080.4 Hz, 1361.1 Hz, 1765.5 Hz).

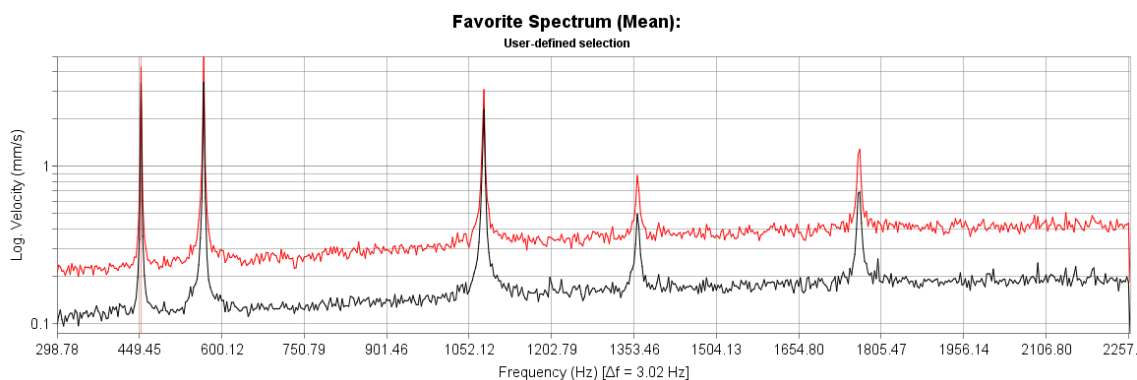


Figure 14: Representation of the first indicator function of the CMIF algorithm

All five mode shapes up to 2 kHz could be extracted. It is particularly noticeable that the X-axis in the camera coordinate system vibrates dominantly, as it accounts for the largest portion of the out-of-plane vibration. This represents the dominant vibration direction. The extracted vibration modes appear very uniform overall (see Figure 15), even in areas of the cover plate where there are few or no clear image features due to large, featureless surfaces.

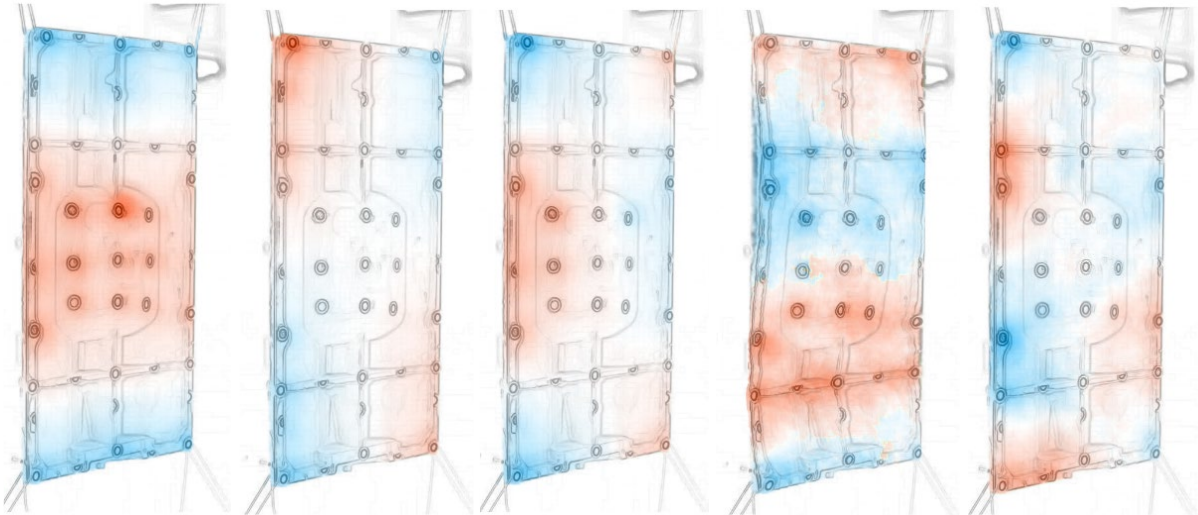


Figure 15: Natural frequencies of the camera measurement at 452.7/567.4/1080.4/1361.1/1765.5 Hz

The measured amplitudes are in the micrometer range, which could only be resolved due to the high subpixel factor of the optical flow. However, as the amplitude decreases, the challenge of accurate detection increases significantly.

7.6 Determination of optimal marker pixels for MAC comparison, reduction of area-based measurement to test geometry

To select the optimal pixels on the 3D markers, the pixels located on the marker that were to be used later for the MAC comparison were first manually identified in the camera image.

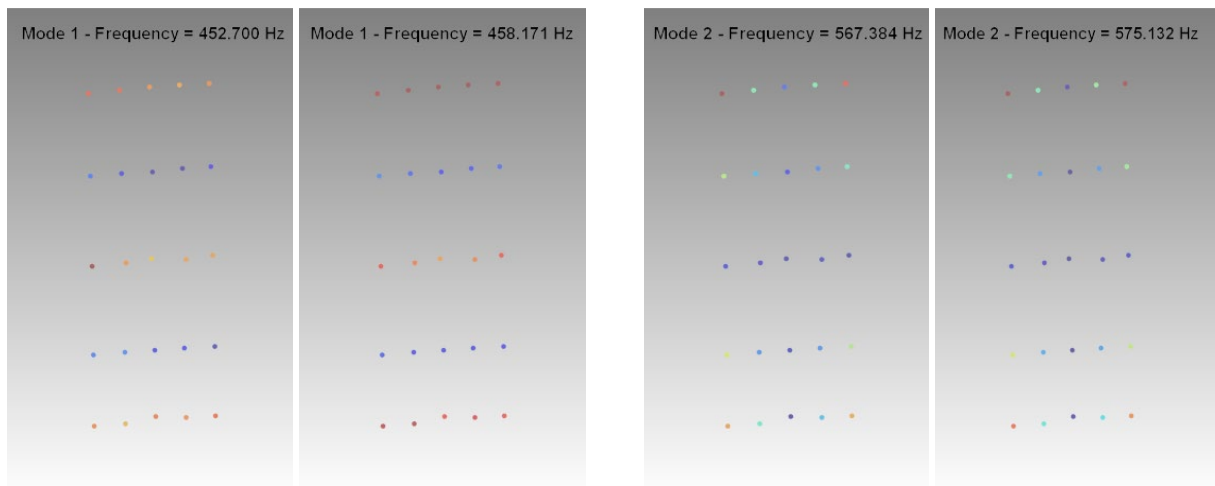


Figure 16: Comparison of the first two eigenmodes with the 25-point geometry: 1.) First eigenmode measurement 2.) First eigenmode FEA 3.) Second eigenmode measurement 4.) Second eigenmode FEA

For each of these starting points, the pixel with the lowest optical flow error was determined within a 7×7 -pixel neighborhood. The size of the neighborhood was chosen such that the selected pixel was guaranteed to lie on the marker. In this way, 25 measurement points with optimal tracking quality were selected, from which a corresponding test geometry with 25 points was derived. Through Z-scaling to adjust the perspective and due to the dominant component in the X-image direction, it was possible to approximate the out-of-

plane component (Z-axis in global coordinates). This measurement geometry was then compared with the corresponding 25 points in the simulation (see Figure 16).

7.7 Test/analysis correlation

The comparison between the experimental modal analysis (EMA/OMA) and the numerical simulation results (FEA) was performed using the ICS.sysval software with the help of the Modal Assurance Criterion (MAC), whereby only the 25 common measurement points according to Figure 9 were considered for determining the MAC value. Table 3a, Table 3b, and Table 4 summarize the results as well as the percentage deviations and MAC values for the first five mode shapes. For the two EMAs, there are practically no differences in the correlation results. The small frequency deviations and high MAC values confirm the very high quality of the FE model.

For the OMA results using optical flow, the frequency deviations are similarly low. However, the MAC values are slightly lower than those of the classical reference measurements, which indicates a slightly lower quality of the corresponding experimental eigenmodes, particularly at higher frequencies (i.e. smaller displacement amplitudes of the vibration). The causes of this are out-of-plane movements, which at small amplitudes contribute more significantly to perspective distortions and scaling changes; the camera resolution, which limits the smallest detectable displacements and thus reduces the signal-to-noise ratio, particularly at higher natural frequencies; and the suspension cables, which influence the measured movements; especially at the edges. A higher camera resolution or increased excitation could improve this situation. Furthermore, interference from out-of-plane motions could be further reduced by selecting an even more optimal camera angle to better capture this motion and by masking or physically damping the suspension cables, particularly at the edges.

Table 3a: Correlation between EMA (acceleration) and FEA (25 measurement points)

No.	EMA Acc. in Hz	FEA in Hz	Dev. in %	MAC in %
1	453.4	458.4	1.1	99.8
2	567.9	573.6	1.0	99.0
3	1081.1	1074.2	-0.6	98.7
4	1364.3	1374.0	0.7	99.5
5	1770.0	1787.6	1.0	98.3

Table 3b: Correlation EMA (laser) / FEA (25 measurement points)

No.	EMA LDV in Hz	FEA in Hz	Dev. in %	MAC in %
1	453.4	458.4	1.1	99.9
2	568.6	573.6	0.9	99.6
3	1081.5	1074.2	-0.7	99.7
4	1363.6	1374.0	0.8	99.7
5	1769.1	1787.6	1.1	99.3

Table 4: Correlation between OMA (optical flow) and FEA (25 measurement points)

No.	OMA Cam. in Hz	FEA in Hz	Dev. in %	MAC in %
1	452.7	458.4	1.3	97.8
2	567.4	573.6	1.1	98.4
3	1080.4	1074.2	-0.6	96.1
4	1361.1	1374.0	1.0	96.7
5	1768.6	1787.6	1.1	94.6

7.8 Damping validation

The comparison of the identified natural frequencies and modal damping ratios obtained from camera-based OMA using optical flow and the reference EMA measurement with a LDV shows an overall very good agreement. The modal damping values also show a high level of consistency between both approaches (see table 5). For the first four modes, the absolute differences between the camera-based and LDV measurements are in the range of approximately 0.01-0.02, which is very small. Considering the significantly more constrained measurement conditions of the camera-based OMA – especially the lower frequency resolution of 1 Hz due to the short recording duration of 1 second, as well as the lower sampling rate compared to the LDV measurement with 0.25 Hz resolution and 6.25 kHz sampling rate – this level of agreement is particularly noteworthy.

It should also be noted that different methods were used for damping estimation. On the optical flow side, damping was determined using the half-power (−3 dB) method in combination with a Lorentzian curve fitting approach, whereas for the LDV data, the damping ratios were extracted using the pole-based estimation method commonly established in EMA. Despite these methodological differences, the results remain highly consistent. Overall, the results demonstrate that camera-based vibration analysis using optical flow is capable of delivering robust and practically relevant modal parameters, even under simplified measurement conditions and despite the methodological differences between OMA and EMA, with results that closely correspond to the LDV reference measurements.

Table 5: Modal Damping between OMA (optical flow) and EMA (LDV)

No.	EMA LDV in Hz	Modal damp. in %	OMA Cam. in Hz	Modal damp. in %
1	453.4	0.09	452.7	0.08
2	568.6	0.09	567.4	0.10
3	1081.5	0.08	1080.4	0.10
4	1363.6	0.14	1361.1	0.15
5	1769.1	0.07	1768.6	0.12

8 Summary and outlook

Using the real-world example of a cover plate, the performance of image-based vibration analysis was investigated, with a specific focus on experimental and operational modal analysis. A comparison with classical methods highlights the advantages, disadvantages, and limitations. The key aspects are:

Advantages of image-based vibration analysis:

- Non-contact measurement (no mass loading and thus no detuning of the test object)
- Simultaneous, high-resolution measurement of all measurement points within the resolution of the camera, resulting in a very good, high-resolution overall impression of the vibration pattern with a short measurement duration (especially compared to high-resolution, sequential laser Doppler vibrometer measurements using a laser scanner)
- Relatively simple measurement setup
- Can be easily combined with common excitation methods
- Good quality, provided that pixels can be tracked with sufficient accuracy based on the image
- Cameras can be selected flexibly depending on the application
- Repeated measurements are unnecessary, as robustness is achieved by averaging over thousands of pixel-based virtual sensors

Disadvantages of image-based vibration analysis:

- Measurement range depends on resolution, lens focal length, and distance
 - Short focal length/long distance → large image area, but lower sensitivity (less pixels/mm)
 - Long focal length/short distance → high sensitivity, but smaller image section
- Minimal movements (< micrometers) require high image quality and, if necessary, a higher excitation level, as movements are measured directly at the displacement level
- When performing vibration measurements with a single camera, movements primarily within the camera plane (in-plane) are captured, e.g., horizontal or vertical deflections of rotating discs, plates, or beams. If depth movements occur simultaneously - i.e., movements toward or away from the camera - these can overlap with the in-plane movements and cannot be clearly separated using a single camera. However, by using a depth image or a stereo camera, the movements can be spatially reconstructed, allowing in-plane and depth movements to be reliably separated and precisely captured.
- In a single-camera measurement, the accuracy of the determined amplitudes depends heavily on the camera perspective. Especially with an inclined arrangement, this can lead to deviations that complicate absolute determination. With a stereo camera measurement or depth images, however, the movements can be reconstructed directly in three-dimensional space, allowing the amplitudes to be determined with absolute accuracy regardless of the camera angle.

Overall, the method of image-based vibration analysis has developed positively in recent years with regard to modal analysis. With increasing camera resolutions and frame rates, further improvements are expected in the future. The disadvantage of pure in-plane measurement could be eliminated by the simultaneous use of multiple cameras two or three. However, accurately determining the geometric positions of the individual cameras relative to one another and to the test object poses a challenge (as is also the case with 3D laser scanning systems, incidentally). Reliable processes and software solutions are required here to realistically enable the application for experimental modal analysis. It should be noted that the limitations of pure in-plane measurements primarily affect the accurate reconstruction of mode shapes and amplitudes, whereas estimated natural frequencies and damping ratios are considerably less sensitive.

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