

## Advancing Digital Image Correlation with Low-Speed Cameras for Structural Dynamics

The limitations of conventional vibration measurement sensors have motivated the development of full-field, non-contact techniques. In this context, Digital Image Correlation (DIC) enables full-field motion tracking by analyzing digital images to extract detailed 3D displacement information of a structure's surface.

This thesis focuses on improving the efficiency and accuracy of DIC for structural dynamic analysis in two challenging contexts: the investigation of nonlinear dynamic behavior in stationary structures with low-speed cameras, and the measurement of rotating machinery dynamics, where large Rigid Body Motion (RBM) poses significant challenges for image processing.

**Chapter 1** introduced the motivation for using DIC in structural dynamics and outlined its advantages over traditional contact-based sensors. Notably, DIC enabled simultaneous measurement at over a large number of points on specimen surface, offering significantly richer spatial information.

Although DIC presents some inherent limitations—such as a low signal-to-noise ratio for small displacements, limited dynamic range, and decorrelation at high rotation angles—this thesis demonstrates that, through tailored methodologies, DIC can be effectively applied to both stationary and rotating structures.

While high-speed DIC provides good dynamic range, its high cost and low resolution motivated the exploration of *low-speed DIC* combined with *downsampling techniques*.

Four downsampling techniques were presented in **Chapter 2**:

- Back-Translation (BT)
- Smoothed Harmonics Analysis (SHA)
- Single Parameter Technique (SPT)
- Circumferential Harmonic Fit (CHF).

These methods allow the signal processing of downsampled data avoiding aliasing, making them crucial for low-speed DIC applications.

In **Chapter 3**, low-speed DIC combined with the BT and SHA methods was applied to two stationary test cases exhibiting *nonlinear dynamic behavior*. The SHA method, which proved to be more accurate than BT, enabled the simultaneous measurement of over 3000 points during each test.

- First, the motion of a *clamped beam excited at 24 Hz and impacting a rigid obstacle* was reconstructed from images sampled at only 23.7 Hz. Despite the low sampling rate, the proposed technique accurately captured the system's response, including both superharmonics and subharmonics of the fundamental frequency, within the 0-150 Hz frequency range, achieving a cross-correlation accuracy of 99.3% when compared with reference Laser Doppler Vibrometer (LDV) measurements.
- Second, tests on a dummy blade were conducted to investigate the effects of centrifugal forces (simulated via an axial preload) when the blade was excited near its resonance frequency. At an excitation of approximately 480 Hz and under a low axial load of 4 kN, nonlinear behavior emerged due to interface friction, resulting in the appearance of superharmonics in the vibration spectrum. The SHA method achieved a reconstruction accuracy of 99.83% when compared with LDV measurements.

These experiments validated the effectiveness of the downsampling methods in reconstructing complex nonlinear vibration responses with low-speed DIC. Although the techniques rely on prior knowledge of the dominant frequencies in the response, this requirement is manageable, as the presence of superharmonics and subharmonics is a typical feature of nonlinear structural behavior. In operational conditions—where excitation forces may not be measurable and the dominant harmonic content of the response is not easily predictable—auxiliary high-frequency sensors (such as microphones, strain gauges, or accelerometers) can be employed to identify the relevant spectral components needed for accurate reconstruction.

**Chapter 4** introduced a novel *Hybrid methodology* for non-contact vibration measurement of *rotating structures* using *high-speed DIC*. Tracking large RBM of rotating structure is challenging with DIC. Hybrid methodology, which combine incremental DIC approach, frame reordering across rotation cycles and RBM compensation, overcomes this limitation. The method requires the displacement between two consecutively analyzed frames to remain within the measurable limits of the DIC algorithm. By sampling the rotation and vibration of the structure at an appropriate frame rate and reordering frames acquired over different rotation cycles, the angular displacement between consecutive frames can be kept within a range suitable for accurate incremental DIC analysis.

This approach enabled impulse response measurements of a rotating plate at 0, 201, 399, and 600 rpm. DIC recorded full-field motion at 9,485 points, and Operational Modal Analysis (OMA) successfully identified 15 resonant frequencies and mode shapes in the 0–350 Hz range.

Importantly, this approach eliminated the need for specialized equipment like derotators or Scanning LDV systems, offering a scalable and practical method for industrial applications.

**Chapter 5** explored *low-speed DIC* for analyzing the dynamics of *rotating bladed disks*. By synchronizing image acquisition at a reference angular position, both high RBM and high sampling rate requirements were overcome. Post-processing with the CHF and SPT downsampling methods allowed extraction of dynamic behavior from the downsampled displacement fields.

The experimental setup involved exciting the first bending mode of a dummy bladed disk with four nodal diameters using magnetic impulses while rotating the disk up to 600 rpm. DIC measured displacements at 27,000 points across the disk surface at a frame rate below 10 Hz.

- The SPT enabled pointwise estimation of modal parameters across the disk, yielding a mean natural frequency of 151.42 Hz and damping ratios between 0.1% and 0.3%. Although the modulation of maximum amplitude observed at the blade tips indicates the presence of mistuning, the method is inherently limited by its single-degree-of-freedom (SDOF) assumption. As a result, it cannot accurately capture the dynamics of the two orthogonal modes, which are split in frequency due to mistuning.
- The CHF method successfully reconstructed the ODS at various rotational speeds, identifying two resonance frequencies at 151.3 Hz and 151.8 Hz. However, due to variability in the excitation force during testing, it was not possible to reliably estimate damping values using this method.

A shift in resonance frequency was observed between the stationary (hammer test) and rotating (DIC) test, attributable to centrifugal stiffening. This shift was consistent with FEM predictions, which estimated the mode's frequency increasing from 149.35 Hz (stationary) to 149.78 Hz (at 600 rpm).

**Chapter 6** concludes the thesis by summarizing the key findings and results obtained.

**Appendix A** provides a brief overview of DIC principles and insights into the MATLAB code used in this thesis for extracting displacement information from images.