Non-Contact Monitoring of Rotating Machinery Using Optimized Camera-Based Stroboscopic Imaging

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ABSTRACT

Monitoring rotating machinery is essential for ensuring reliability and reducing maintenance costs. Cameras have recently gained attention as non-contact sensors due to their high spatial resolution and minimal interference. However, high-speed rotation introduces challenges such as motion blur, aliasing, and reliance on expensive high-speed cameras. This study proposes a camera-only stroboscopic imaging method for real-time, non-contact monitoring. By capturing frames at fixed angular intervals without external synchronization and applying optimized object tracking and phase-based optical flow (POF), the system estimates full-field, sub-pixel displacements. Phase-locked displacement data is used to identify rotor faults. Experimental validation on a lab-scale blade system confirms accurate displacement measurement and effective fault detection, offering a practical solution for aerospace, wind, and industrial applications.

INTRODUCTION

Monitoring rotating machinery is critical for ensuring reliability, minimizing maintenance, and preventing failures [1]. These systems are vital in aerospace, energy, and manufacturing, where structural integrity ensures safety and performance [2]. Conventional monitoring typically uses contact sensors like accelerometers and strain gauges, which, despite their accuracy, require complex installation and can interfere with machine operation, especially at high speeds [3]. To overcome these drawbacks, non-contact techniques using cameras and laser sensors have been investigated. Yet, high-speed rotation introduces motion blur, aliasing, and synchronization challenges [4]. High-precision methods such as Digital Image Correlation (DIC) and Laser Doppler Vibrometers (LDVs) face limitations: DIC requires high-contrast patterns, and LDVs are costly and limited to single-point measurements [5]. Phase-Based Optical Flow

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(POF) achieves sub-pixel resolution but suffers under blur and aliasing [6]. Stroboscopic imaging helps reduce blur but usually depends on high-speed cameras and external synchronization, restricting industrial use. Current solutions remain constrained by motion artifacts, cost, and coverage, limiting fault detection like bolt loosening, imbalance, and misalignment [7]. This study addresses these issues with a camera-only stroboscopic imaging technique combined with POF. The approach enables full-field, sub-pixel displacement estimation and phase-based fault classification—without external synchronization or high-speed hardware. Targeting rotating blades in aerospace and energy systems, the method is experimentally validated on a lab-scale system with known defects. This work offers a cost-effective, scalable framework for real-time monitoring of rotating machinery.

SENSING AND PROCESSING PRINCIPLES

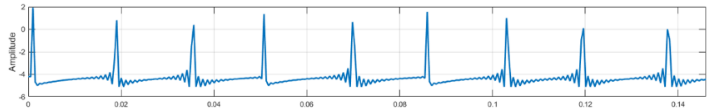
Stroboscopic Imaging and Phase Synchronization

To reduce motion blur and enable consistent observation of high-speed rotating structures, this study utilizes a stroboscopic imaging technique based on phase-locked synchronization. The motor's electrical signal is acquired and analyzed in the frequency domain using a Fast Fourier Transform (FFT), from which the dominant rotational frequency is estimated as:

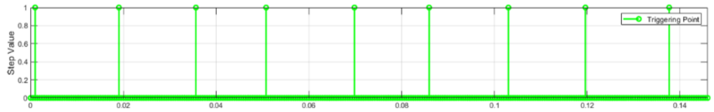
$$f = \frac{i_{max} F_s}{N_p} \times \frac{1}{2N_b} \tag{1}$$

Figure 1 illustrates this process. Subfigure (a) shows the raw motor signal sampled at high resolution. From this, discrete trigger points are extracted at equal intervals to form the phase-locked step signal in (b). These triggers correspond to specific rotational phases and are used to synchronize the camera's shutter. Subfigure (c) presents the

(a) Motor Signal



(b) Discrete Step Signal = Phase-locked Signal



(c) Generated Sin Wave

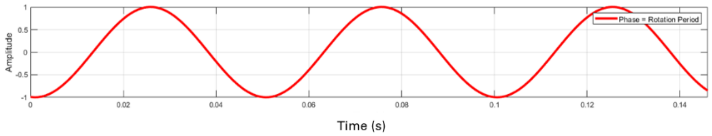


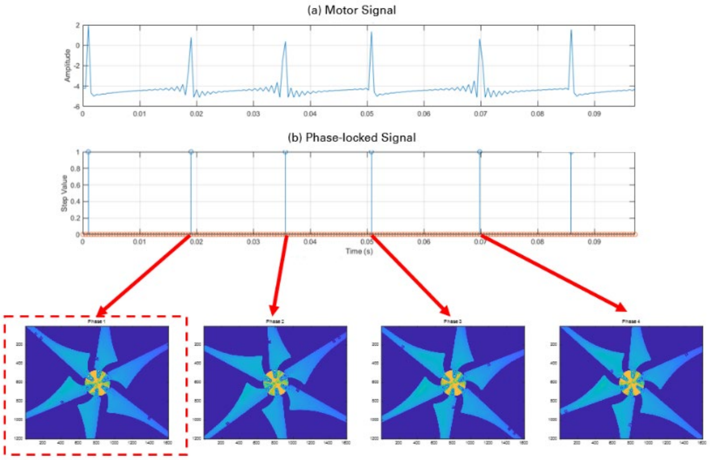
Figure 1. Phase-locked signal generation using motor signals: (a) receiving signals at equal intervals within the rotation of the motor; (b) generating discrete signals based on (a); (c) inverting RPM and generating corresponding sine-wave signals.

reconstructed sinusoidal signal, which defines the rotational phase over time and guides the timing of image capture. This phase-locked strategy enables images to be acquired only at predefined angular positions, reducing redundant data while maintaining phase consistency. The resulting stroboscopic image sequence appears stationary but preserves subtle pixel-level displacements for further analysis.

Displacement Estimation via Phase-Based Optical Flow

Phase-Based Optical Flow (POF) estimates fine-scale structural displacements by analyzing local phase changes in sequential images. Originally proposed by Gautama et al. [6], POF differs from conventional intensity-based methods by using phase information obtained through spatial filtering [8], allowing sub-pixel motion estimation that is robust to lighting variations and noise. In this framework, each image pair is processed using a multi-scale, multi-orientation complex Gabor filter bank [10], producing local amplitude and phase components. The local phase $\varphi(\mathrm{x}, \mathrm{y}, \mathrm{t})$, which is highly sensitive to motion, is used to compute displacement between frames. Figure 2 illustrates this process. The raw motor signal (a) is transformed into a phase-locked trigger signal (b), used to capture images at fixed angular positions. Frames corresponding to the same phase across multiple rotations are selected (c), and phase-aligned stroboscopic sequences are constructed (d). This setup enables consistent motion tracking over time. Under the assumption of temporal phase constancy at a given spatial location, the motion vector along the phase gradient direction is estimated as:

$$\boldsymbol{v}_c = \frac{-\varphi_t}{(\varphi_x^2 + \varphi_y^2)}\left(\varphi_x, \varphi_y\right) \tag{2}$$


(a) Motor Signal

(b) Phase-locked Signal

(c) Stroboscopic Image

(d) Captured Image Using Phase-locked Signal

Figure 2. Process of creating a stroboscopic image: (a) raw motor data; (b) phase-locked signal based on (a); (c) stroboscopic image with a specific phase selected; (d) frame in the image captured by triggering on the phase-locked signal.

where φ_x, φ_y are spatial phase gradients, φ_t is the temporal phase shift. By applying this formulation to the phase-aligned frames, high-resolution displacement fields can be obtained, serving as the foundation for subsequent fault analysis. To resolve directional ambiguity caused by the aperture problem, multiple Gabor filters at varying orientations are used. The resulting motion estimates are fused using the intersection-of-constraints (IOC) method, enabling robust full-field displacement estimation. Recent improvements in filter parameter optimization have enhanced performance under noisy or low-light conditions, making POF particularly suitable for structural motion analysis in rotating machinery.

Tangential Motion Tracking and Feature Extraction

In this study, tangential displacement of a rotating structure is estimated using phase-based optical flow (POF) applied to stroboscopic image sequences. A cross-shaped marker is employed to track motion orthogonal to its orientation, enabling accurate extraction of 2D displacement components—particularly in the tangential direction relative to the rotation axis [10]. Tangential displacement is directly proportional to rotational speed and serves as a key indicator of dynamic balance, stability, and structural defects such as imbalance, misalignment, or localized anomalies. In the proposed method, phase-aligned frames are analyzed using POF to detect sub-pixel shifts in the tangential direction. These displacements are aggregated across matching phases, enabling high-resolution motion analysis. The resulting tangential displacement field is used to assess the operational condition of the rotor. Figure 3 illustrates this process, with displacement vectors shown along the circular path of the rotating blade, visualized via pixel-wise color gradients near the marker.

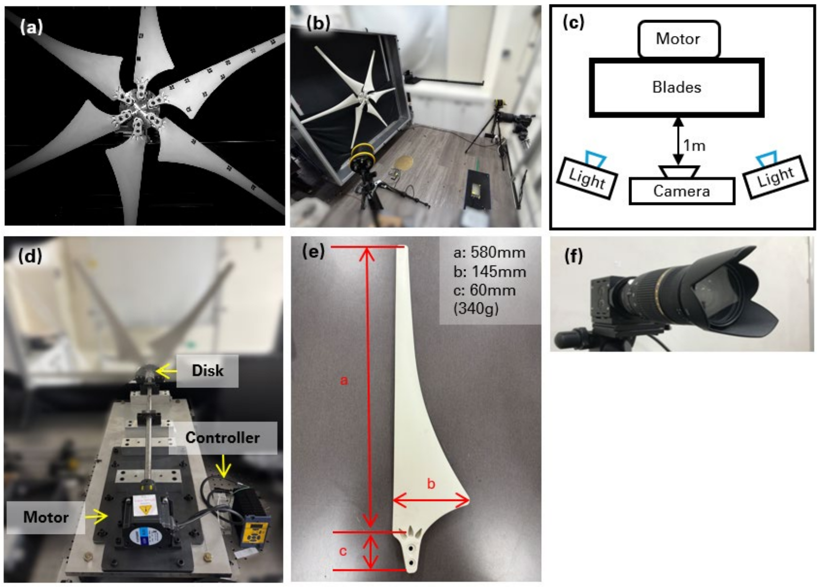
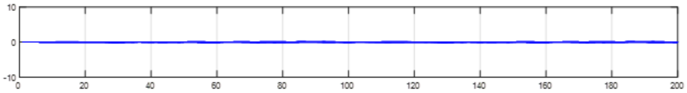
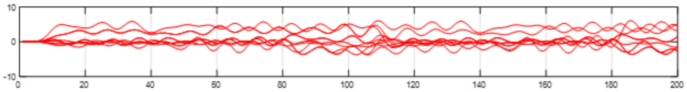


Figure 3. Experimental setup: a) Blade and rotor from the front; b) Side view of experimental setup: blade, camera, lights, etc.; c) Schematic diagram of experimental setup; d) Experimental structure viewed from the opposite side of rotation: motor, controller, disk, etc.; e) Detailed spec. of blade used in the experiment; f) Camera, NX8.

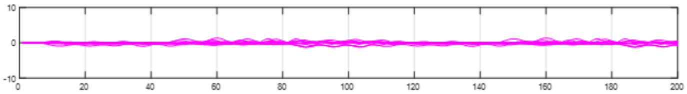
(a) Healthy



(b) Bolt Loosening



(c) Imbalance



(d) Misalignment

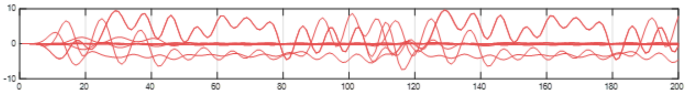


Figure 4. Displacement graphs with bandpass applied: (a) Healthy condition; (b) Bolt loosening; (c) Imbalance; (d) Misalignment.

EXPERIMENTAL VERIFICATION

Experimental Setup

The experimental setup, shown in Fig. 3, was designed to evaluate micro-displacement measurement and defect detection in rotating blades using stroboscopic imaging and phase-based optical flow (POF). The test rig features a six-blade rotor with carbon-fiber-reinforced blades, each 580 mm long and weighing 340 g, driven by a

BLDC motor operating at 120 RPM. The motor is mounted on a shaft and bearing assembly to replicate realistic rotational conditions. Image acquisition was performed

using an IDT NX8 high-speed camera synchronized via phase-locked triggering. The camera was set to an exposure time of 200 μs, resolution of 1600 × 1200 pixels, and frame rate of 1000 FPS. To minimize motion blur and ensure consistent illumination, three high-intensity LED light sources were employed.

Analysis

Displacement signals extracted from stroboscopic image sequences were analyzed to assess fault-specific characteristics under various structural anomalies. Initial comparison of unfiltered data revealed that bolt loosening produced displacements up to 10 pixels, and mass imbalance showed approximately threefold increases relative to the healthy state. Shaft misalignment resulted in irregular displacement patterns, occasionally reaching large amplitudes similar to bolt loosening but also exhibiting near-normal values, indicating higher variability. To enhance signal clarity and highlight periodic features, a bandpass filter was applied to the displacement data. As shown in Fig. 4, the filtered signals retain the characteristic patterns associated with each defect type. Bolt loosening and misalignment show amplified and irregular oscillations, while imbalance exhibits relatively smooth but larger-amplitude motion compared to

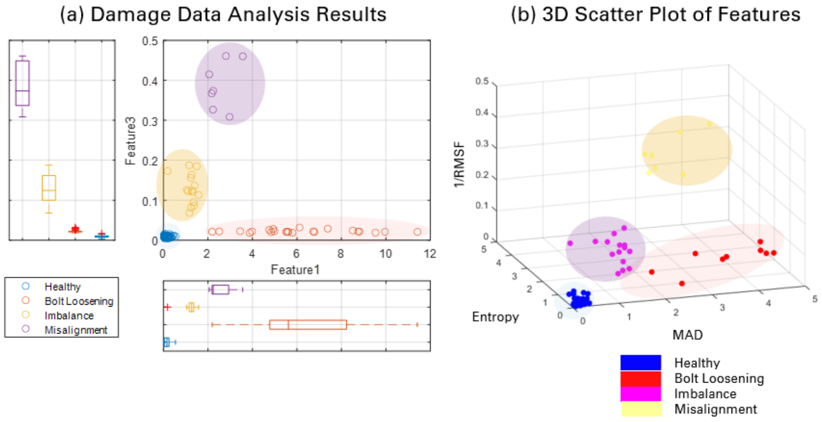


Figure 5. Scatter plot of damage type classification using characteristic factors: (a) Damage Data Analysis Results; (b) 3D Scatter Plot of Features.

the healthy condition, which remains flat. This filtering step improves signal interpretability for subsequent frequency-domain analysis. Using the filtered data, envelope spectrum and cepstrum analyses were performed. The envelope spectrum revealed dominant vibration components near 2 Hz in defect cases, with bolt loosening and misalignment conditions exhibiting over tenfold increases in amplitude compared to the healthy state. Cepstrum analysis showed consistent trends, albeit with smaller differences in magnitude, offering complementary insight into signal periodicity and

structural dynamics. Based on these analyses, key statistical features were extracted, including MAD (from filtered data), entropy (from envelope spectrum), and RMSF (from cepstrum). Feature selection was conducted using ROC curves, and the top-performing features were used for fault classification. Fisher Discriminant Analysis (FDA) successfully separated healthy and defective states by identifying an optimal decision boundary, while multi-class FDA visualizations further distinguished different fault types. Fig. 5. presents the final damage classification results using the selected characteristic features. Subfigure (a) shows the two-dimensional distribution of MAD and RMSF, clearly separating damage types through clustering. Subfigure (b) visualizes the three-dimensional feature space (MAD, entropy, and RMSF), further enhancing fault separability. Each fault condition forms a distinct cluster, confirming the effectiveness of the proposed feature set and classification approach in accurately identifying structural anomalies.

CONCLUSION AND FUTURE WORK

This study proposed a novel camera-only stroboscopic imaging technique combined with phase-based optical flow (POF) for real-time, non-contact monitoring of rotating machinery. By capturing images at consistent rotational phases without external synchronization or high-speed cameras, the method enabled full-field, sub-pixel displacement measurements. Through experimental validation on a laboratory-scale blade system, the technique demonstrated high accuracy and reliability in detecting structural anomalies, such as bolt loosening, mass imbalance, and shaft misalignment. The integration of displacement-based feature extraction and classification using Fisher Discriminant Analysis (FDA) further confirmed the system's capability to effectively differentiate between healthy and defective conditions. This approach offers a cost-effective, scalable solution for practical condition monitoring applications across aerospace, wind energy, and industrial machinery sectors. Future work will focus on expanding the technique to higher rotational speeds and more complex rotating structures. Additional efforts will also aim to simplify the imaging process by developing marker-free stroboscopic methods and to enhance fault classification performance through advanced signal processing and machine learning approaches under realistic operational conditions.

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