Intuitive and Less-Supervised Structural Damage Detection Using Phase-Based Vibration Imaging

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ABSTRACT

Numerous structural vibration monitoring techniques have been developed to identify structural operational conditions or structural damage. However, a high-level supervision from experts is usually required especially for applications on complicated structures. Cameras, as a noncontact sensor, have emerged as a powerful tool for measuring the full-field vibration of complex structures due to its advantages over the traditional contact sensors, such as flexible positioning, simultaneous multi-points tracking, and high-spatial resolution. However, extracting key information from the large amount of data from video sequences can be challenging. In this paper, we propose an improved phase-based optical flow method to efficiently estimate the full-field displacement, enabling visualization of the vibration energy distribution in a less-supervised manner. The method consists of several steps. First, multiple Gabor filters are applied to extract the local phases at different scales and in different directions. The phase variations and spatial gradients are then used to estimate displacement components at each pixel. Sub-pixel level accuracy is achieved by rejecting unreliable components using confidence measures and then integrating them into the motion. The user only needs to provide inputs for two thresholds of confidence measures. Second, based on the extracted full-field displacements, the structural vibration is transformed into a series of images using feature extraction techniques, such as mean absolute deviation, which scales the amplitude of vibration level, and/or frequency filtering which visualizes operational deflection shapes in near real-time. Finally, a nonlinearity weighted local area mapping algorithm is proposed to detect anomalies present in a structure, which is done by calculating the difference in the full-field feature map between healthy and tested states. To validate our approach, we conducted on experiment on an air compressor and compared the results with those measured by accelerometers. The results showed that the proposed vibration imaging technique can clearly identify damage and indicate its potential for various structural dynamics applications.

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INTRODUCTION

Cameras are widely used in various applications, including structural health monitoring and condition monitoring, due to their advantages such as low cost, remote sensing, and high spatial-resolution measurements [1]. Camera-based techniques for dynamic response measurements can be broadly classified into two categories, image intensity-based and phase-based displacement measurements. Image intensity refers to the amount of light that hits a pixel, while the phase is extracted from an image convolved with a pair of quadrature filters with finite supports [2]. The phase-based approach has gained attention due to its improved accuracy in revealing subtle motions [3]. Several studies have demonstrated that phases obtained through multi-scale and multi-direction decomposition contain valuable motion information and can enhance the accuracy of intensity-based methods for structural damage detection [4].

The complex Gabor filter is a tool for generating local image phases. In authors' previous works [5, 6], optimal filter and marker designs based on Gabor filters were conducted to achieve improved phase-based displacement measurements. However, single-point measurements have their limitations as they focus on the specific local area and require extensive human supervision for parameter tuning and/or marker placement. A full-field vibration analysis, called vibration imaging, was developed to help identify regions that warrant detailed measurements, especially in unknown structures [7].

The proposed techniques aim to perform the intuitive and less-supervised damage detection based on the vibration imaging and unique mapping techniques. The vibration imaging minimizes the need for user supervision in extracting the full-field displacements for extracting vibration feature maps. Improved confidence measures, including phase nonlinearity and filter responses, are employed to reject unreliable displacement components caused by nonlinear phase and image noise. Subsequently, full-field displacements are computed by integrating all displacement components using intersection of constraints (IOC) and vector average (VA). Additionally, image registration and nonlinearity weighted local area mapping are performed to visualize the defect area by calculating the Euclidean distance between features of the healthy and damaged states, even when the structures have different initial positions in image coordinates. Experimental validations were conducted to demonstrate the accuracy of the proposed damage detection.

PHASE-BASED VIBRATION IMAGING

The proposed scheme for full-field displacement measurements and the vibration imaging consists of several steps, as illustrated in Fig. 1 [7]. As the first step, Gaussian smoothing gradient is applied to reduce the image noises and extract the edge information since the homogeneous area is not favorable to motion estimation especially for the phase-based techniques.

Second, Gabor filters are employed to extract local phase information at various scales and directions, enabling robust estimation of displacements. Two sets of filters all with identical 1-octave bandwidths but differing modulation frequencies are used to extract phase. This design helps prevent substantial overlap in the radial direction. Additionally, employing five filters for each modulation frequency aids in avoiding significant angular overlap. As a result, the reduced overlap enhances the independence

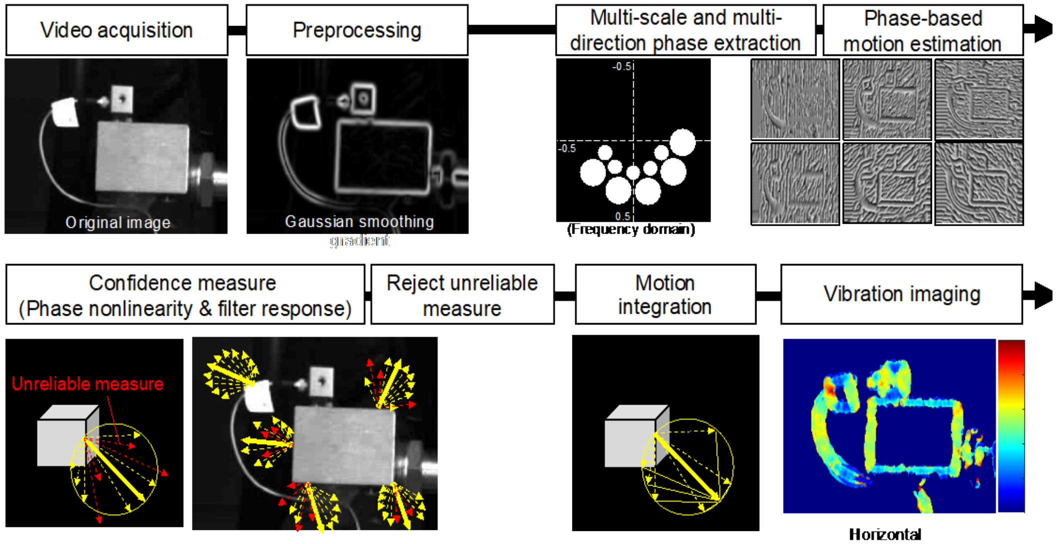

Figure 1. Working flow of the proposed phase-based vibration imaging [7].

of lateral motion integration measurements, and concurrently decreases computational cost.

Third, two confidence measures, namely phase nonlinearity and filter responses, are employed to reject unreliable displacement vectors at each pixel. For each pixel at a certain frame, a multiple displacement vectors can be obtained. However, not all of these displacement components are reliable for a pixel on a local vibrating object. For instance, a point measurement on a straight edge may primarily provide reliable displacement components with directions close to the edge's normal direction only. Therefore, it becomes critical to reject any unreliable components using specific criteria or criteria-based measures.

Phase nonlinearities that indicate measurement errors for phase-based motion estimations were studied by Miao et al. [6, 7]. Precise measurements depend on a stable phase with a nearly constant spatial phase gradient. The phase nonlinearity is measured by comparing the displacement results estimated from the measured spatial phase gradients and their mean. In addition to phase nonlinearity quantification, we also assess the filter responses as an additional confidence measure.

Finally, all the valid displacement components are integrated using intersection of constraints (IOC) and vector average (VA) to avoid the aperture problem. IOC aims to find the optimal intersection point of constraint lines formed by observed displacement components from multiple filters, while VA involves averaging valid displacement vectors. IOC generally provides more accurate results with enough reliable displacement components, while VA offers stability with a small number of vectors. In this study, both methods are utilized based on a selection criterion: IOC is utilized when three or more reliable displacement components are available, and VA is employed for the remaining pixels. This combination of IOC and VA provides a robust approach for motion integration, allowing for accurate and stable estimation of full-field displacements in various scenarios.

The full-field displacements obtained through combined motion integration methods, can be further analyzed using feature extraction techniques, as described in the next section.

VIBRATION IMAING AND STRUCTURAL DAMAGE DETECTION

In structural health monitoring application using cameras, there are additional complexity arising from collective sensing of numerous pixels surpassing the accuracy of traditional contact sensors. Traditional algorithms that rely on statistical distribution comparison of one-dimensional time-series data may prove inefficient when dealing with high-spatial resolution vibration information obtained from individual pixels. Moreover, correlating signals from multiple videos using the same pixel position can be challenging due to potential misalignments between the physical structure and the image coordinates. To navigate these challenges, the proposed nonlinearity weighted local area mapping technique leverages structural damage-sensitive features to compare vibration information between images even when the positions in image coordinates vary. By incorporating nonlinearity weights, the technique places emphasis on the most relevant and informative areas within the images, facilitating accurate comparison and detection of structural damage.

Nonlinearity-Weighted Local Area Mapping

Section 2 introduces the use of 2D full-field vibration measurement techniques along with confidence measures. These methods enable the automatic selection of reliable pixels from a large pool of pixels. By accurately measuring the vibration information, damage-sensitive features are determined, allowing for effective damage detection. However, when monitoring a target structure over an extended period, the image coordinates may vary across different images, as illustrated in Figure 2. To address this issue, image registration is performed between the reference frames of each video. This registration process involves matching image features and obtaining a transformation matrix. The transformation matrix is then applied to correct the vibration feature maps for each measurement. Additionally, a nonlinearity weighted filter is employed to perform local area mapping and compare the modified feature maps of different states. Compared to conventional local mapping techniques that depend on average or maximum values within a predefined window, the proposed approach introduces a kernel based on the inverse of the pixel-wise nonlinearity. This kernel enables weighted averaging, resulting in a more robust and accurate mapping outcome. This approach enables the visualization of full-field vibrations in the structure through vibration features. It facilitates effective comparisons and damage detection, even in scenarios where coordinate variations exist across different images.

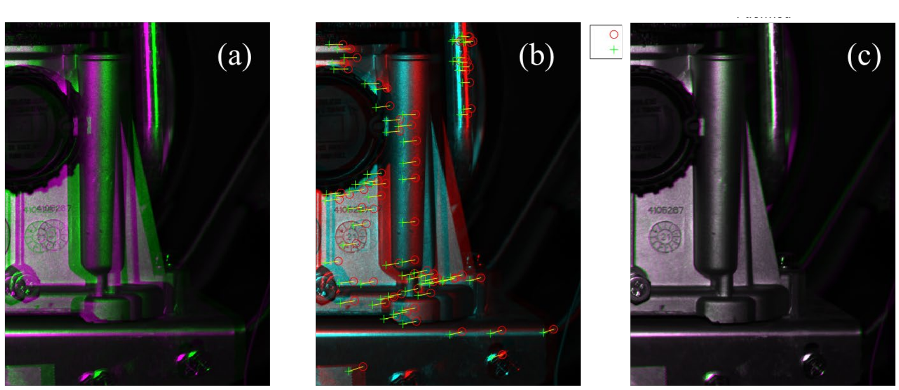

Figure 2. Example of image registration for damage detection: (a) image misalignment between two images; (b) matched image features; (c) registration result.

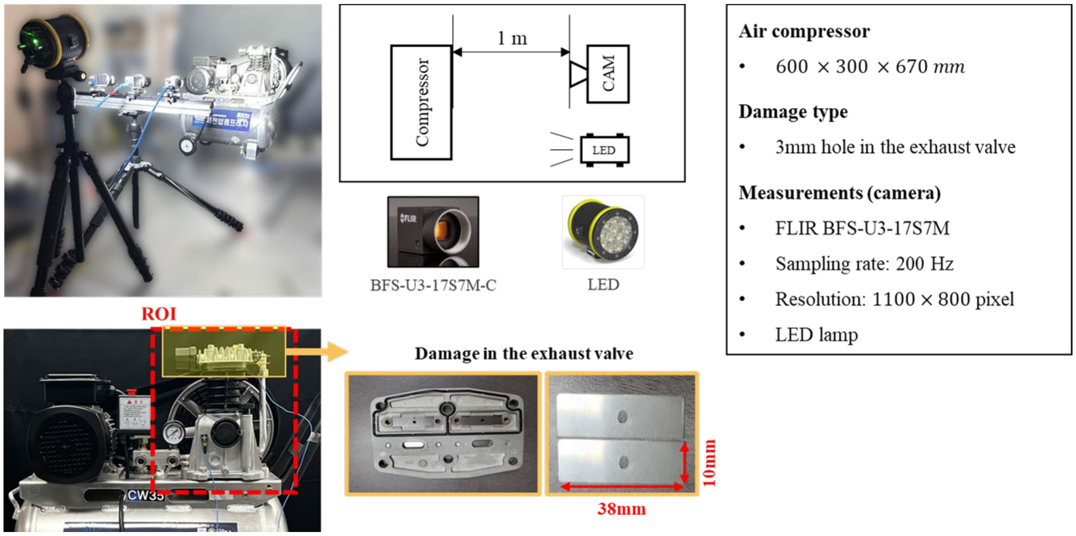

Figure 3. Experimental set-up

EXPERIMENTAL VALIDATION

Experimental Set-Up

Experimental validation is conducted on an air compressor to demonstrate the effectiveness of the full-field vibration measurement and imaging techniques. To simulate structural damage, a 3mm hole is intentionally created in the exhaust valve. The purpose of this simulated damage is to evaluate the ability of the techniques to accurately detect and visualize structural anomalies. During the experiments, the full-field vibration measurements are performed using the proposed techniques, capturing the dynamic response of the air compressor. The vibration imaging technique is then applied to generate vibration feature maps, highlighting areas of interest related to the simulated damage.

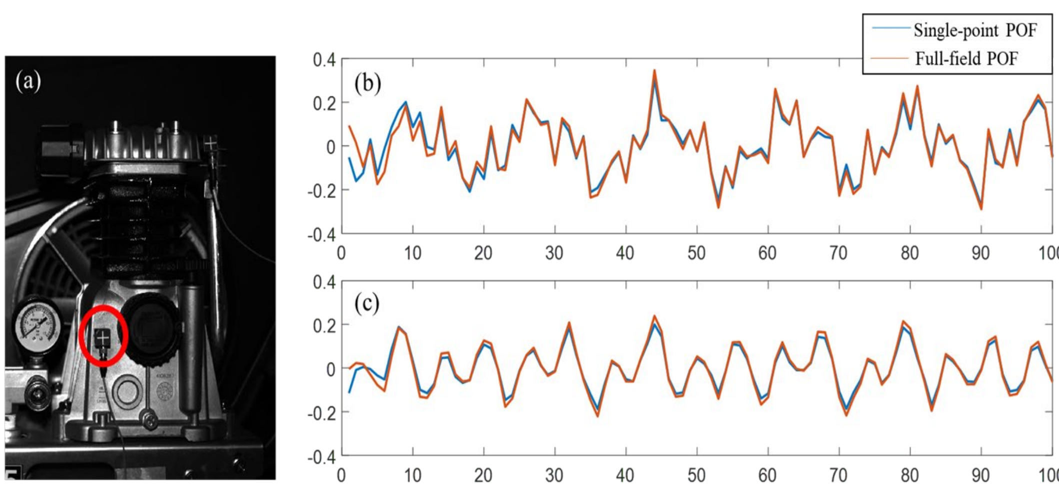

Figure 4. Comparison between two POF methods (a) Captured image and measurement point; (b) measurement in horizontal direction; (c) measurement in vertical direction.

Full-field Displacement Measurement

The results of displacement measurement at a single point using an optimized Gabor filter have been previously validated in [5, 6]. In order to demonstrate the effectiveness of full-field measurement, a comparison is made between the measurement result at a single point and the measurement result at that same point after applying the proposed full-field measurement technique. This comparison is depicted in Figure 4, which shows the differences and improvements achieved by transitioning from single-point measurement to full-field measurement.

Vibration Imaging and Damage Detection

DAMAGE SENSITIVE FEATURE IMAGING

Figure 5 illustrates the visualization of vibration amplitudes in the x direction for both the healthy state and the damaged structure using the proposed full-field measurement technique. The visualization provides a graphical representation of the vibrational characteristics in these two conditions. To facilitate effective damage detection, further analysis of the vibration signals was conducted. This analysis involved performing frequency analysis and distribution analysis of the signal features. Through these analyses, specific features that are sensitive to structural damage were identified.

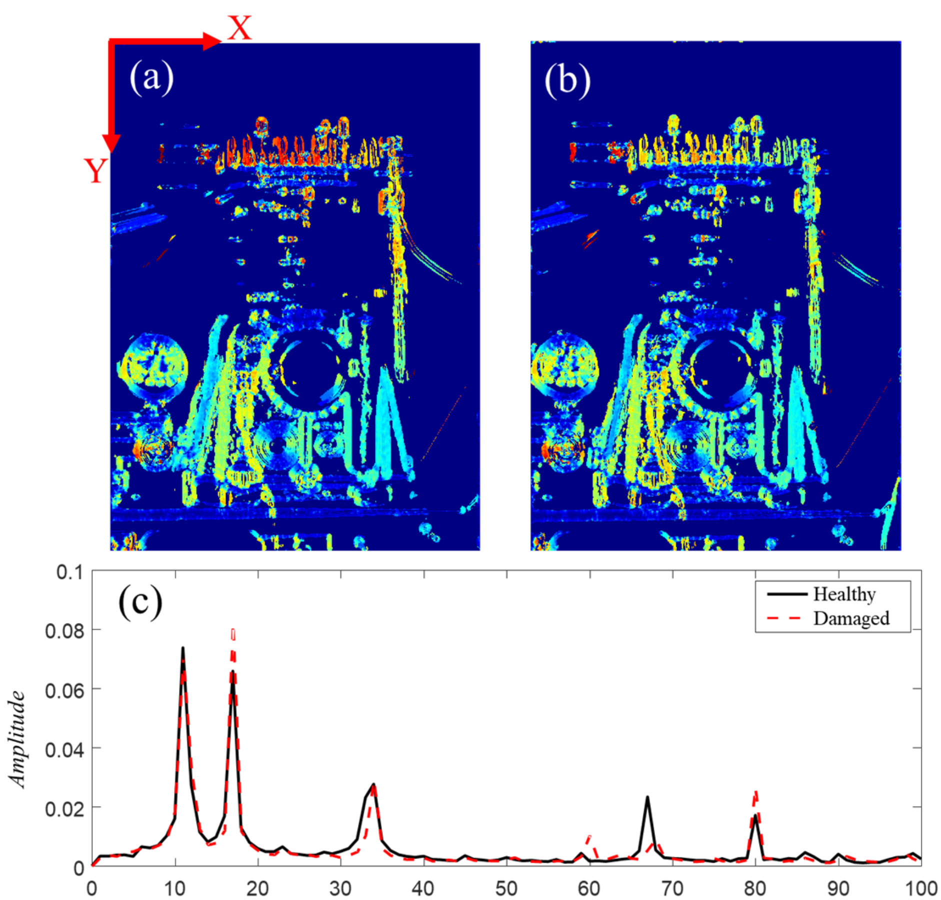

Figure 5. (a) Vibration amplitude map of healthy state in x direction; (b) vibration amplitude map of damaged state in x direction ;(c) comparison of frequency domain between healthy and damaged state.

Among the identified features, the mean absolute deviation (MAD) value was selected as the most suitable damage-sensitive feature within a specific frequency range, approximately 68 Hz. The MAD value serves as an indicator of the overall vibration amplitude, providing a concise representation of the structural condition. By utilizing the damage-sensitive feature, the proposed technique enhances the ability to detect and quantify the extent of damage in the structure.

DAMAGE DETECTION USING LOCAL VIBRATION FEATURE MAPPING

Figure 6 (a-b) illustrates the visualization of defect areas through direct comparison by calculating the feature distance between the damage-sensitive features of each state. However, it is important to note that, due to misalignment between the images, it is difficult to make an effective comparison. As a result, the direct comparison may not fully capture the differences in vibration patterns caused by the defects. In contrast, Figure 6 (c-d) presents the results of the proposed nonlinearity weighted local feature mapping technique. This technique effectively addresses the issue of misalignment and enhances the visualization the defect areas with high accuracy. By incorporating the nonlinearity weighted approach, the technique highlights the regions that exhibit significant differences in vibration between the healthy state and the damaged structure. The nonlinearity weighted local feature mapping technique offers a more reliable and

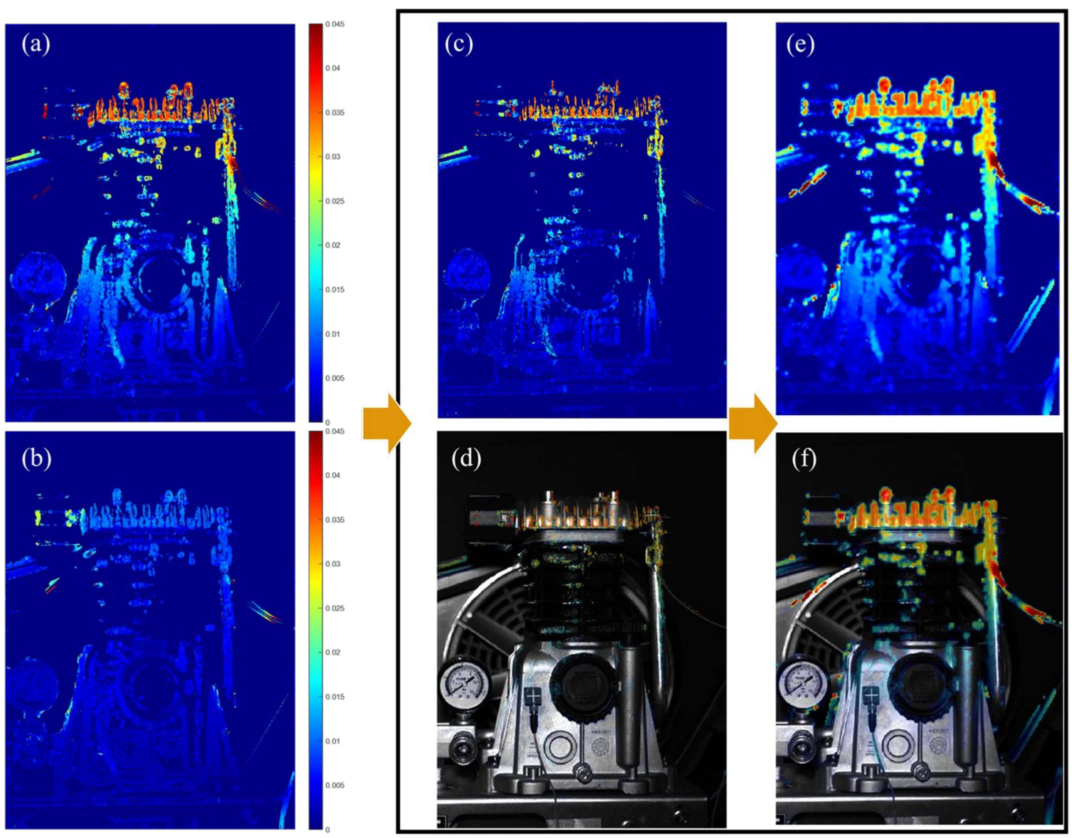

Figure 6. Damage visualization results by feature distance between healthy and damaged state after bandpass filtering: (a) feature value of healthy state; (b) feature value of damaged state; (c-d) damage-sensitive feature distance image; (e-f) feature distance using nonlinearity weighted local feature mapping.

precise visualization of the defect areas in the exhaust components. Overall, the proposed technique improves the visualization of differences in vibration patterns caused by defects, enhancing the ability to detect and analyze structural damage.

CONCLUSION

In this study, we utilized multiple Gabor filters to extract phase information from different directions and scales, enabling to capture a comprehensive view of the structural vibration. To ensure the reliability of our measurements, we introduced two confidence measures, namely nonlinearity and filter responses. These techniques allowed to filter out unreliable measurements and obtain accurate full-field displacement results. By visualizing the displacement information across the entire image, we achieved a more comprehensive and reliable full-field displacement measurements.

Moreover, we leveraged the proposed techniques to select damage-sensitive features for structural vibration analysis and detection of structural defects. To address potential errors arising from misalignment between images, image registration techniques and a nonlinearity weighted local area mapping techniques are also suggested. We validated that our proposed approach enables more precise visualization of defect areas compared to pixel-based signal processing methods by experiments on an air compressor. Overall, our study contributes to the advancement of full-field measurement techniques and damage detection in structural health monitoring. The proposed methods offer improved accuracy, efficiency, and visualization capabilities, enhancing our ability to analyze and diagnose structural defects in various applications.

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