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# Multi-point vibration measurement and mode magnification of civil structures using video-based motion processing

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ABSTRACT

Image-based vibration measurement has gained increased attentions in civil and construction communities. A recent video-based motion magnification method was developed to measure and visualize small structure motions. This new approach presents a potential for low-cost vibration measurement and mode shape identification. Pilot studies using this approach on simple rigid body structures were reported. Its validity on complex outdoor structures has not been investigated. In this study, a non-contact video-based approach for multi-point vibration measurement and mode magnification is introduced. The proposed approach can output a full-field vibration map that increases the efficiency of the current structural health monitoring (SHM) practice. The multi-point approach is developed based on the local phases which also fill the gap of the existing intensity-based multi-point vibration measurement. As an extension of the phase-based motion magnification, the multi-point measurement result is then integrated with the maximum likelihood estimation (MLE) to estimate the magnified frequency bands at each identified structure mode for operational deflection shape (ODS) visualization. This proposed method was tested in both indoor and outdoor environments for validation. The results show that using the developed method, mode frequencies and mode shapes of multiple points in complex structures can be simultaneously measured. And vibrations in each mode can be visualized separately after magnification.

## 1. Introduction

In the last decades, vibration-based modal analysis was one of the most widely used techniques in structural health monitoring (SHM) of civil infrastructures. The fundamental idea is that the damage, aging and environmental-induced deterioration will result in the change of the physical properties of structures (e.g. mass, damping and stiffness) that can be detected by measuring the abnormal responses of structural vibration [1]. Current vibration measurement can be classified as contact and non-contact methods. The contact method requires engineers to manually instrument contact transducers, such as linear variable displacement transducers (LVDT), accelerometers or strain gages, at locations of interest to observe the amplitudes and frequencies of structural oscillations [2]. The contact sensors can detect vibrations at high accuracy, long dynamic ranges and being able to identify structural damage without external excitations [3]. However, the physical installation process is cumbersome, and the added mass of loadings may also change the natural behaviors of the lightweight inspection targets that limit the practicability of this method in many disciplines [4]. Such limitations can be attenuated by using the non-contact measurement approaches. Currently, the most widely used non-contact sensors include Laser Doppler Vibrometry (LDV), synthetic aperture radar (SAR), ultra-sound and vision system. The vision system relies on camcorder to record time series image sequence which has the advantages of low-cost, texture rich and easy to implement. With the recent development of image processing and computer vision techniques, the accuracy and robustness of the vision-based approach has been greatly improved which make it applicable for field measurements [5].

Tracking algorithm is one of the most widely used vision approaches for vibration measurement. It relies on edge detection, digital image correlation (DIC), pattern matching or object recognition to extract features in each image, and measures the displacements by counting the movements of these features in pixels over time [6–8]. The existing studies used feature-rich markers mounted on the inspection targets to measure the vibration of in-service structures [9,10]. Due to the size and geometry of the markers are known, the structural displacements were estimated by directly counting the movements of these markers. However, the markers still need to be manually placed on the hard-to-reach parts of a structure, the convenience of using such non-contact method is reduced. Recent study suggested that by using objects' own features, marker-less approaches can reach similar level of accuracy as

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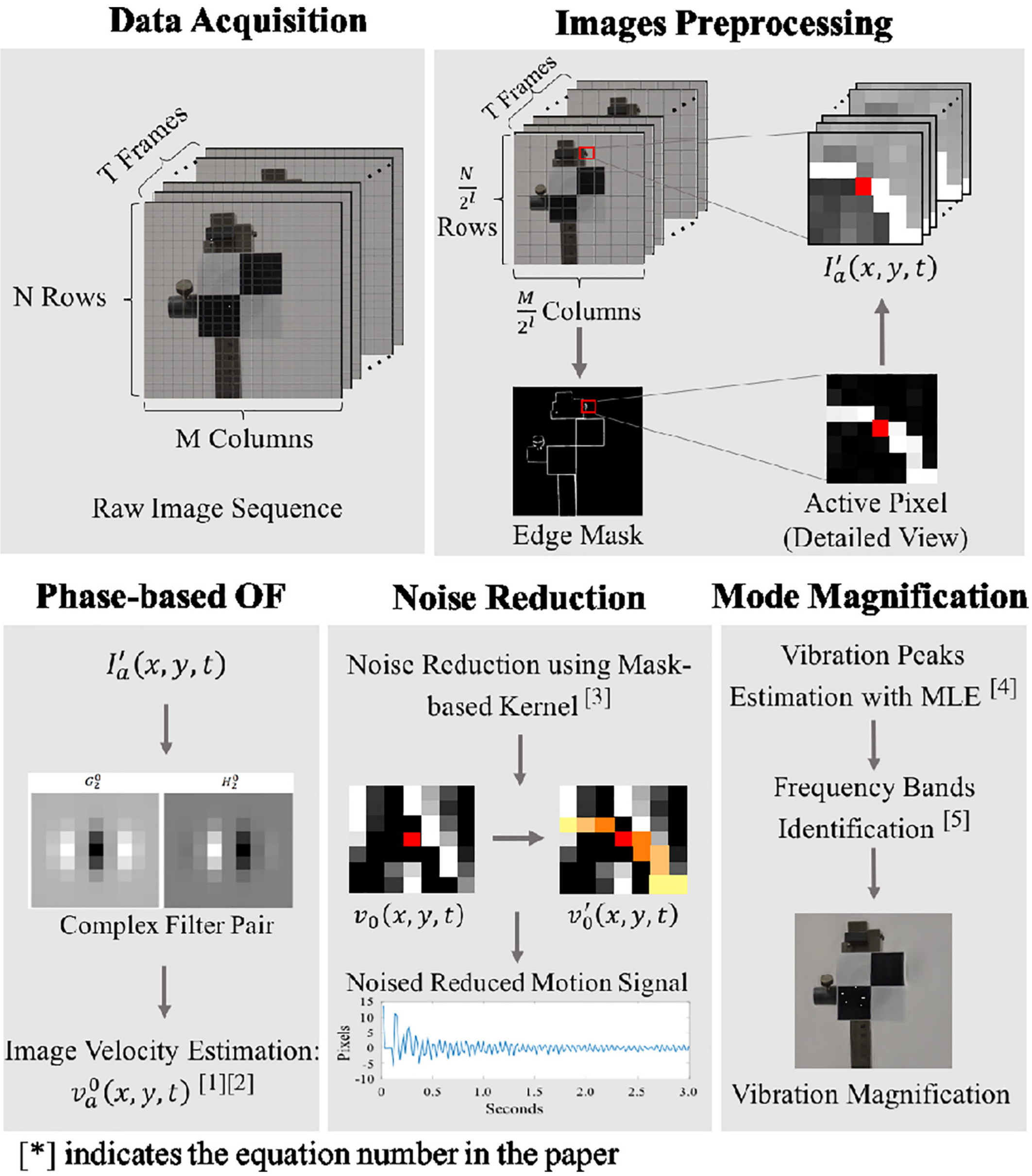

**Fig. 1.** Semantic diagram of the proposed method.

the marker-based one for field applications [11]. For example, the bridge decks, cables, beams and hangers always show high gradient in textures where the displacements can be measured by tracking these features over time [12,13]. The tracking method has the advantages of direct displacement measurement. However, it requires notable structural motions at feature points. Motions without apparent pixel-level changes make the method unsuitable, which is the major drawback of this method.

Comparing to the tracking method, optical flow can achieve subpixel accuracy by estimating the apparent velocity of movements in images. The method assumed that the image illuminations are constant and all intensity variations are linearly related to the motions of objects [14]. The existing studies showed that optical flow can monitor the subpixel vibrations even for long distance measurement [15]. Recently, a technique called virtual visual sensor (VVS), which follows the same assumption as optical flow, was developed [16]. The method is able to efficiently capture the vibration frequency by counting the intensity changes at each pixel [17]. However, without in-plane reference, such method fails to estimate the magnitude of structural vibration because no direct connection has been found between the pixel luminosity changes and vibration amplitudes [18].

Lately, researchers in Massachusetts Institute of Technology (MIT) introduced a novel yet simple approach, called Eulerian video magnification, to magnify subtle motions in a video so they can be perceptible to naked eyes [19]. The method multiples a magnification factor with the intensity value change to amplify the motions in the video. However, simply amplifying the intensity variations will also increase the noise powers that results in artificial results in the reconstructed video. To reduce this noise floor, a phase-based motion magnification method was developed which uses local phases to encode the temporal motions [20]. Compare to the intensity strength, motion estimated by phases is more robust to environmental noise, such as the image illumination, perspective and surface pattern changes [21].

In [22,23], Chen et al. applied the noncontact phase-based optical flow to measure the vibrations of simple laboratory-scale structures. The measured vibration peaks are then used to identify the frequency bands of motion magnification such that the operating deflection shapes (ODS) of these structures are visualized. [24] evaluated the