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Blind identification of full-field vibration modes of output-only structures from uniformly-sampled, possibly temporally-aliased (sub-Nyquist), video measurements

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ABSTRACT

Enhancing the spatial and temporal resolution of vibration measurements and modal analysis could significantly benefit dynamic modelling, analysis, and health monitoring of structures. For example, spatially high-density mode shapes are critical for accurate vibration-based damage localization. In experimental or operational modal analysis, higher (frequency) modes, which may be outside the frequency range of the measurement, contain local structural features that can improve damage localization as well as the construction and updating of the modal-based dynamic model of the structure. In general, the resolution of vibration measurements can be increased by enhanced hardware. Traditional vibration measurement sensors such as accelerometers have high-frequency sampling capacity; however, they are discrete point-wise sensors only providing sparse, low spatial sensing resolution measurements, while dense deployment to achieve high spatial resolution is expensive and results in the mass-loading effect and modification of structure's surface. Non-contact measurement methods such as scanning laser vibrometers provide high spatial and temporal resolution sensing capacity; however, they make measurements sequentially that requires considerable acquisition time. As an alternative non-contact method, digital video cameras are relatively low-cost, agile, and provide high spatial resolution, simultaneous, measurements. Combined with vision based algorithms (e.g., image correlation or template matching, optical flow, etc.), video camera based measurements have been successfully used for experimental and operational vibration measurement and subsequent modal analysis. However, the sampling frequency of most affordable digital cameras is limited to 30–60 Hz, while high-speed cameras for higher frequency vibration measurements are extremely costly. This work develops a computational algorithm capable of performing vibration measurement at a uniform sampling frequency lower than what is required by the Shannon-Nyquist sampling theorem for output-only modal analysis. In particular, the spatio-temporal uncoupling property of the modal expansion of structural vibration responses enables a

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direct modal decoupling of the temporally-aliased vibration measurements by existing output-only modal analysis methods, yielding (full-field) mode shapes estimation directly. Then the signal aliasing properties in modal analysis is exploited to estimate the modal frequencies and damping ratios. The proposed method is validated by laboratory experiments where output-only modal identification is conducted on temporally-aliased acceleration responses and particularly the temporally-aliased video measurements of bench-scale structures, including a three-story building structure and a cantilever beam.

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1. Introduction

Modal analysis is the primary structural dynamics technique for modeling and analysis of structural vibration. Identifying the experimental modal parameters (modal frequencies, damping ratio, and mode shapes) from the vibration measurements are essential for dynamic modelling and analysis, correlating and updating mathematical model for response prediction, and vibration-based health monitoring of civil, mechanical, and aerospace structures [1–3]. Experimental and operational modal analysis are two general classes of methods used to identify the modal parameters from vibration measurements. Experimental modal analysis refers to methods that use both measured inputs (excitation) and outputs (response) to the structure, while operational or output-only modal analysis methods rely only on response measurements. Operational modal analysis is considered a useful alternative for larger-scale structures (subjected to broadband excitation which is usually available such as traffic and wind excitation on bridges) where controllable excitation is difficult to apply on the structure or the operating excitation is challenging to measure.

Enhancing the temporal and spatial resolution of vibration measurements for modal analysis could significantly benefit structural dynamics modelling and analysis. For establishing a structure's dynamic model based on the experimental modal parameters, incorporating more spatial measurement points or more higher (frequency) modes contributes to a more refined and accurate dynamic model, which is essential for accurate prediction of dynamic response and comprehensive analysis of the dynamic behaviors under a broader spectrum of loads. Higher-resolution vibration measurements and modal information are also critical for the success of the vibration based structural health monitoring (SHM). For example, a comparative study [4] showed that the spatial resolution of the sensor measurement critically limits the effectiveness of a family of popular mode shape or mode shape curvature based damage detection and localization methods. For another, higher frequency modes capture more local features of the structure and thus contain more information of structural damage which is typically a local phenomenon [3].

Improving the resolution of vibration measurements and modal analysis may be accomplished by enhancing measurement hardware. Traditional vibration measurement devices for experimental and operational modal analysis such as strain sensors and accelerometers have high sampling frequency capacities. However, these discrete point-wise sensors only provide sparse, low spatial sensing resolution measurements, because their dense deployment to achieve high spatial resolution is not only expensive, but also results in mass loading the structure [1,5] and significant modification of structure's surface. Many non-contact measurement techniques, such as displacements made with scanning laser vibrometers [6–8] and electronic speckle pattern interferometry (ESPI) and holographic interferometry [9–12], generally provide high spatial and temporal resolution sensing capacity without the need to install sensors on the structure or inducing the mass-loading effect. However, these measurement devices are relatively expensive and sensitive to ambient vibration. In addition, scanning laser vibrometers perform measurements sequentially, which could be time and labor intensive when the desired measurement areas are large.

As an alternative non-contact measurement method, digital video cameras are relatively low-cost, agile (easy and rapid setup), and provide simultaneous measurements with very high spatial resolution. Combined with image processing algorithms (e.g., image correlation [13] or template matching and optical flow [14]), video camera based measurements have been successfully used for experimental modal analysis [15–21], obtaining full field modal information. With a stereo video camera setup (or using a time-of-flight type of cameras [22]), it is possible to obtain 3-dimensional mode shapes in experimental modal testing. Recently, phase-based video motion estimation technique [23–25] has been explored to perform output-only modal identification without the need of installing high-contrast markers or speckle paints on the structure's surface [26,27]. This technique enables extraction and visualization of full field modal parameters in a relatively efficient and automated manner [27]. However, one significant bottleneck of most digital video cameras is that the sampling frequency is limited to around 30 or 60 Hz, causing temporally-aliased measurements for high-frequency vibration. On the other hand, high-speed cameras are extremely expensive (tens of thousands of U.S. dollars) for wide applications in vibration measurements. In order for video camera based measurement techniques to gain wide acceptance for truly full-field, high-resolution modal analysis, it is desirable to develop novel methods that could improve the temporal sampling resolution of the video cameras in an affordable manner.

This study proposes a computational algorithm for output-only modal identification using the possibly temporally-aliased vibration measurements (particularly videos) by explicitly exploiting the signal aliasing properties in modal analysis.