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Lifting approach to simplify output-only continuous-scan laser vibrometry

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ABSTRACT

Continuous-scan laser Doppler vibrometry (CSLDV) can greatly accelerate modal testing by continuously sweeping the measuring laser over a structure, effectively capturing its response at tens or even hundreds of points along the laser path. Several techniques have been devised to process CSLDV measurements from structures under controlled input. The authors recently extended CSLDV to the case where the input forces are unmeasured random white noise, using the harmonic power spectrum of a time periodic system. The harmonic power spectrum is analogous to the power spectrum used in the identification of time invariant systems, but with many additional harmonics for each mode, requiring an additional effort in modal parameter estimation. This paper presents a variant on the harmonic power spectrum, proposing a simplified algorithm based on the lifting approach. Lifting causes all sideband peaks in the harmonic power spectrum to collapse into a single peak in the range from zero to half of the scan frequency, so the spectra are far easier to interpret. The proposed algorithm is first evaluated on a simulated beam, and found to give results that are comparable with those obtained by the harmonic power spectrum method, yet the data reduction with the lifting approach is much simpler. This algorithm is then employed to identify the first several modes of a parked wind turbine under wind excitation, using a new long range remote sensing vibrometer. The speckle noise is found to be remarkably small even at a standoff distance of 77 m and a surface scan velocity of 500 m/s without any surface treatment.

1. Introduction

A laser Doppler vibrometer uses the Doppler shift in the frequency of laser light to detect the velocity at a point along the direction of incident laser [1]. Conventionally, the laser is moved by a pair of mirrors from one point to another to take measurements at discrete locations. In continuous-scan laser Doppler vibrometry (CSLDV), the laser beam continuously sweeps over a structure while recording the response along the scan path. This greatly reduces the time required for modal testing, especially for structures with low frequency, lightly damped modes, e.g. wind turbine blades, which require long time records at each measurement point. If the structure changes with time or the inputs are difficult to replicate, CSLDV allows greatly increased spatial detail to be identified in a short amount of time. This leads to insights into the dynamics of

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Nomenclature

A	system matrix
B	control or input matrix
$C(t)$	periodic output matrix due to moving laser
y	measured output using CSLDV
l	integer describing the offset of a harmonic peak
n	integer giving the order of a harmonic in a Fourier series expansion
r	integer referring to a particular mode
ψ_r	rth mode shape of the underlying time invariant system
ω_r	rth natural frequency of the underlying time invariant system
ζ_r	rth damping ratio of the underlying time invariant system
λ_r	rth eigenvalue of the underlying time invariant system
T_A	fundamental period of the linear time periodic system
ω_A	fundamental frequency of the linear time periodic system or scan frequency
$Y_n(\omega)$	nth harmonic of the exponentially modulated periodic output in the frequency domain
$\mathbf{Y}_n(\omega)$	collection of exponentially modulated periodic output signals
$S_{\mathbf{YY}}(\omega)$	harmonic power spectrum
$C_{r,n}$	nth Fourier coefficient in the Fourier coefficient mode vector
$\bar{\mathbf{C}}_{r,l}$	Fourier coefficient mode vector at the lth harmonic of the rth mode
$\mathbf{W}_r$	scale factor related to the random input
$\mathbf{A}_{r,l}$	residue of the lth harmonic of the rth mode in harmonic power spectrum
$R[k]$	linear harmonic correlation function
$R^+[k]$	positive linear harmonic correlation function
$H_{\mathbf{YY}}(\omega)$	positive harmonic power spectrum
$R_m^+[k]$	lifted linear harmonic correlation function at the mth point
$\mathbf{R}_\mathbf{m}^+(\omega)$	FFT of positive harmonic correlation function for the mth point on the laser path
$\mathbf{Res}_{\mathbf{r,m}}(\omega)$	residue matrix of the rth mode identified from the lifted correlation function at mth point

a structure that may be helpful when performing model correlation and updating [2], damage detection and many other applications.

However, due to the continuously moving measurement location, it is more complicated to process CSLDV measurements than those from a conventional point by point test. Several algorithms have been developed to extract natural frequencies and mode shapes from CSLDV since the 1990s. Among them, Ewins and Stanbridge et al. modeled the operating deflection shape as a continuous polynomial function of the laser position. The recorded vibration shape using CSLDV was treated as being modulated by the moving laser position, which leads to sideband harmonics in the spectrum that are separated by the scan frequency. They showed that the amplitudes at those harmonics are related to the polynomial coefficients by a transformation matrix. Once the polynomial coefficients are extracted, the mode shapes can be reconstructed using the known laser path. This method is very effective and straightforward, and they have used it to reconstruct the mode shapes of a structure using sinusoidal [3], impact [4], and pseudo-random excitation [5]. However, if the operational shape along the laser path is not smooth, high order polynomial coefficients are necessary to accurately describe the shape. The precision of this method is limited by the number of harmonics that stand out above the noise floor in the measured spectrum. Laser speckle noise is generated as the coherent laser scatters from a rough surface, which causes a random distributed intensity of the backscattered laser [6]. The noise level is affected by many factors, including the mirror configuration [7], surface quality [8] and surface scan velocity [9]. An in-depth study of speckle noise in laser Doppler vibrometry can be found in [10]. In general, speckle noise in CSLDV can be alleviated by using a low scan frequency (smaller than 10 Hz) on a surface covered with retro-reflective tape.

Allen et al. later proposed an alternative ‘discrete’ lifting approach [10]. Using this approach, the responses at the same location along the laser path are grouped together. The reorganized responses then appear to be from a set of pseudo-transducers distributed along the scan path, except that each sensor samples only one time over each scan period, and there is a constant time delay between the measurements at each point. As a result, according to the sampling theorem, all the modes of the system and their harmonics are aliased to the range from zero to half of the scan frequency. This approach produces a set of spectra that are mathematically equivalent to a single-input multiple-output system, and hence conventional modal analysis software can be used to extract the modal parameters from the CSLDV measurement. In [11] the authors used the lifting approach to extract the natural frequencies and mass-normalized mode shapes of a free–free beam under impact excitation. They demonstrated that, ideally, one would choose the scan frequency to be larger than twice the maximum frequency of interest, but often this is not possible. The maximum scan frequency is restricted by the mechanical scanners (up to 500 Hz). The nonlinearity of the scanner and the laser speckle noise also increase with the scan frequency. So, the scan frequency is chosen to ensure that the modes do not overlap after being aliased to the band of half of the scan frequency. Therefore, the lifting approach is more suitable for measuring structures whose natural frequencies are only a few hundreds Hz.

All of these methods require that the force exciting the structure be either impulsive or some known, carefully controlled function (e.g. sinusoidal). Sometimes it is difficult or even impossible to directly measure the dynamic load on a structure,