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Concrete damage mapping combining laser scanning vibrometry, dynamic response modeling, and ordinary kriging regression

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Abstract

The present study deals with the application of laser scanning vibrometry in monitoring of concrete dynamic behavior and evaluation of dynamic response changes when structural damage occurs. Concrete specimens that exhibit different types of damage are excited artificially using a vibration shaker actuator, and velocity response is acquired on multiple points by employing a PSV-500H laser scanning vibrometer. As optical interaction between laser beam and concrete surfaces yields speckle-related noise to measured velocity response, multi-peak frequency response functions are employed for the simulation of measured spectra and smoothing of induced noise. Surface mapping of concrete elements dynamic modes is achieved by exploiting ordinary kriging regression. Proposed experimental arrangement and data post-processing are attained to illustrate efficiently concrete surficial dynamic response and reveal simultaneously velocity map discontinuities that correspond to crack existence.

KEYWORDS

concrete nondestructive control, laser scanning vibrometry, structural damage mapping

1 | INTRODUCTION

Reliable maintenance of constructions demands timely detection of structural damage and effective restoration of them. For the last 20 years, nondestructive testing (NDT) methods have improved essentially the structure inspection procedures, allowing a holistic approach to structural integrity monitoring. In case of concrete constructions, several NDT techniques have been implemented, namely, ultrasonic pulse velocity measurement, evaluation of hammer impact dynamic response (impact-echo), thermography, and ground penetration radar.[1] Furthermore, piezoelectric sensors[2-6] and optical fibers[7,8] have been employed in development of innovative NDT techniques that have contributed to the design of remote, permanent, multi-sensor, and web-based systems for the health monitoring of concrete structures. Especially, wireless piezoelectric sensor-based monitoring systems have provided innovative and integrated solutions for concrete elements structural health monitoring and crack hazard likelihood assessment.[4-6]

Although widespread application of the abovementioned methods, all of them suffer from the disadvantage of physical contact requirement between the monitoring construction and the sensing parts of the equipment. This condition may inhibit the measuring procedure in cases where access to construction members is difficult or any contact with the observing subject is forbidden. Moving machine elements, technical equipment that operates in high-pressure and high-temperature conditions, cultural artifacts, and monuments are some examples where physical contact is prohibited because either health safety issues or the danger of an accidental damage occurs during the monitoring procedure.

Laser scanning vibrometry (LSV) is a contemporary technique that allows the standoff and noncontact surveying of an engineering structure vibration velocity on a mesh of monitoring points. The principle that governs LSV method relies on Doppler effect and the physical relation of each monitoring point vibration velocity with the frequency shift that a laser beam undergoes when there are incidents on structure's vibrating surface.[9] Multi-point acquisition of vibration velocity allows the spatial screening and mapping of constructional members vibration modes. As vibration patterns reflect in several cases the structural continuity of a mechanical body, the presence of mechanical flaws like cracks and voids can be imprinted in vibration velocity spatial distribution, as distinctive abnormalities.[10-12]

LSV has been successfully employed in engineering research for the evaluation of dynamic behavior and structural integrity of metallic constructional elements like plates and beams,[13,14] rotating machine elements,[15] and aircraft wings.[16] Monitoring of wave propagation in thin metallic plates and their interaction with structural flaws is another essential discipline where LSV method has been effectively employed for the diagnosis of structural damage.[17-19] In the field of concrete NDT, LSV has been implemented for the assessment of structural condition and coherence between concrete and steel reinforcement,[20] flaw positioning in concrete elements,[21,22] monitoring of damage evolution in beam specimens under bending and cubic specimens under compression,[23] and fiber-reinforced plastic (FRP) layer de-bonding diagnosis.[24]

The present study focuses on the application of LSV method in monitoring of concrete dynamic response and evaluation of changes, which emerge when damage occurs. Concrete beam specimens that suffer from different types of damage were fabricated and surveyed by employing a PSV-500H scanning vibrometer supplied by Polytec GmbH.[25] Vibration velocity Fourier spectra were acquired on monitoring points. Laser speckle-related noise is an essential problematic issue that encountered in LSV-based monitoring.[9,11,12] In the present study, speckle noise was normalized by simulating experimentally acquired monitoring signatures with analytical frequency response functions (FRFs). Concrete specimens' vibration shape mapping was performed by ordinary kriging regression, applying a spatial statistic correlation among the normalized spectral data.[26] Results of the present work provide adequate evidences that the proposed integrated measuring and post-processing procedure can efficiently reveal the dynamic response of a concrete element. Furthermore, structural damage has been detected and positioned accurately by evaluating the damage-related abnormalities in velocity spectral maps.

2 | LASER SCANNING VIBROMETRY

LSV is an advancement of laser Doppler vibrometry (LDV) that allows a multi-point remote and noncontact measuring of structure vibration velocity signals. Figure 1 shows schematically the functional principles of LDV. The vibration velocity of a monitoring point $V_{r,p}$ is given by the following equation[9]:

$$V_{r,p} = \frac{1}{2} f_r = \frac{1}{2}(f_{r2} - f_{r0}) \ , p = 1 : N_p, \tag{1}$$

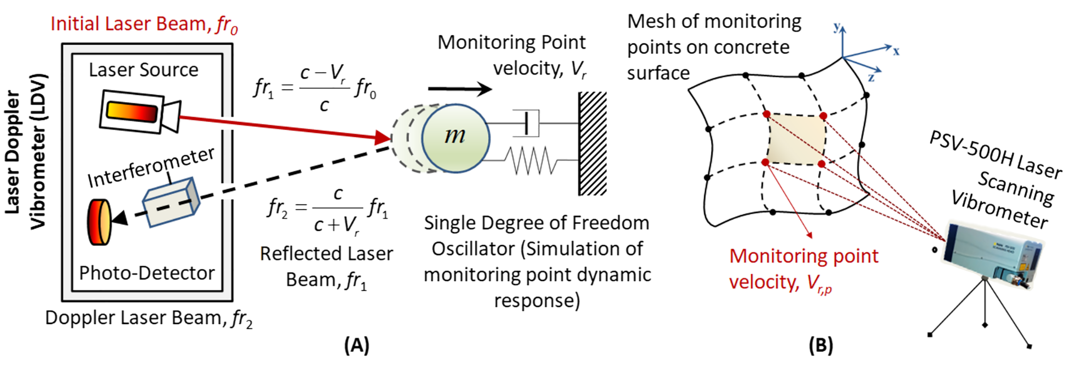

FIGURE 1 . (A) Laser Doppler vibrometry principle and (B) laser scanning vibrometry arrangement

where λ is the wavelength of Laser beam, Δf_r is the frequency shift between initial laser beam frequency f_{r0} and Doppler-changed laser beam frequency f_{r2}, and N_p is the number of monitoring point. Variable c, which is termed in Figure 1, is the velocity of laser beam, which is equal with the speed of light. A Polytec PSV-500H[25] LSV device operates laser sources with emission wavelength equal to 633 nm, which corresponds to an electromagnetic wave frequency of 474 THz. Laser electromagnetic frequency is several orders higher than expectable Doppler frequency shift. For this reason, frequency shift Δf_r is measured via a Mach-Zehnder–based interferometer arrangement combined with an acousto-optic modulator.[9,25]

3 | ACQUIRED VELOCITY DATA PROCESSING AND VIBRATION MAPPING

The LSV PSV-500H measures velocity signal on each monitoring point in time domain following a sampling frequency FS, defined by user. Velocity spectra derive from Fourier transform of velocity signals on N frequency points $f_{r,i} = 0.5FS(i-1)/(N-1)$, $i = 1{:}N$. Number of Fourier transform frequency points depends on the sampling frequency FS and the length of velocity signal measurement vectors.[23] Acquired data normalization and mapping procedure are presented in Figure 2 flowchart.

3.1 | Laser speckle noise normalization

Concrete exhibits rough surfaces that are characterized by low reflectivity. This condition combined with concrete microstructure inhomogeneity induces dephasing of laser beam and create speckle-related noise.[9,11] Speckle noise is emerged in velocity Fourier signatures as resonance pseudo-peaks that obscure in several cases the dynamic features of investigated construction. The normalization of speckle-related peaks is addressed with the simulation of measured velocity signatures ${V_{r,p}}^{\text{meas}}$ by the following analytical multi-peak modal FRF:

$$V_{r,p}^{\text{sim}}(,\mathbf{c}) = \sum_{j=1}^{M} \frac{A_{s,j}}{\sqrt{\left({}_{0,j}^{2} - {}^{2}\right)^{2} + {}_{0,jj}^{22\;\;2}}}, \tag{2}$$

where $\mathbf{c}_{(1\times 3M)} = [A_{s,1} \ldots A_{s,j} \ldots A_{s,M}\ \omega_{0,1} \ldots \omega_{0,j} \ldots \omega_{0,M}\ \eta_1 \ldots \eta_j \ldots \eta_M]$ analytical FRF parameter vectors; $A_{s,j}$, $\omega_{0,j}$, and η_j are the spectral acceleration amplitude, angular resonate frequency, and mechanical loss factor of jth modal component of analytical FRF, respectively; ω is the angular frequency; and M is the number of peak-mode components. FRF model (Equation (2)) corresponds to the response of a multi-degree of freedom (MDOF) mechanical oscillator, a physical analogous that can efficiently approaches the vibration modes of real structural systems. Parameter vector $\mathbf{c}$ is calculated via nonlinear constrained least square method by minimizing square residual error sum as Equation (3) shows.

$$\min_{c}\left\{\sum_{i=1}^{N}\left[V_{r,p}^{\text{sim}}(\omega_i,\mathbf{c}) - V_{r,ip}^{\text{meas}}\right]^2\right\}, \text{subject} to \begin{matrix}\mathbf{c} > 0\\ \eta_j < 1\end{matrix}. \tag{3}$$

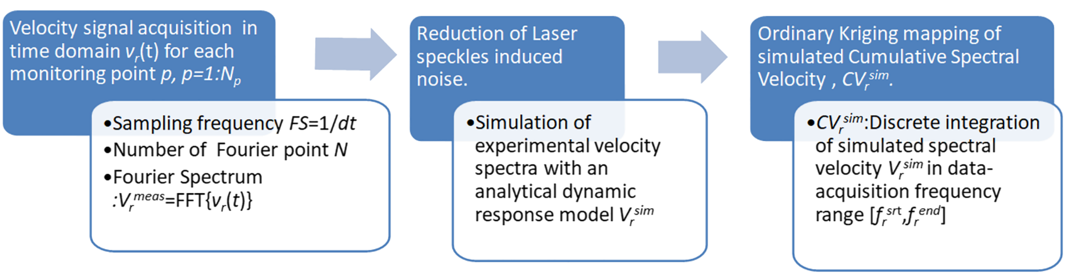

FIGURE 2 Measurements and spectral velocity post-processing flowchart

3.2 | Ordinary kriging mapping

Ordinary kriging is a widespread estimation technique for the assessment of the unknown value of monitoring variable on points where no measurements have been taken. Estimation relies on the determination of spatial statistical correlation among the measured values.[26] In the context of the present study, mapping-monitoring variable was termed the cumulative spectral velocity (CSV), which for each monitoring point p (Figure 1) is given by the following equation:

$$CV_{r,p}^{\mathrm{sim}} = \int_{f_r^{srt}}^{f_r^{\mathrm{end}}} V_{r,p}^{\mathrm{sim}}(\omega,\mathbf{c})df_r \cong \frac{FS}{N}\sum_{i=1}^{N} V_{r,p}^{\mathrm{sim}}(\omega_i,\mathbf{c}), \tag{4}$$

where $CV_{r,p}{}^{\mathrm{sim}}$ has units of acceleration (mm/s^2) and is calculated by discrete integration of simulation de-noised spectra $V_{r,p}{}^{\mathrm{sim}}$ (Equation (2)) in an frequency range $[f_r^{\mathrm{srt}}, f_r^{\mathrm{end}}]$.

4 | EXPERIMENT, RESULTS, AND DISCUSSION

The experimental procedure was conducted by scanning the surficial vibration velocity of concrete beam specimens with dimensions 750 × 150 × 90 mm, which experienced different damage states. For the purpose of this research, the PSV-500H equipment was employed. Two of the beam specimens were suffered by shear and tensile cracks respectively as it is shown in Figure 3B,C. Shear cracked beam was reinforced by axial steel rebar and had been a failure under 3-point bending loading. Tensile cracked beam also had been failure under bending loading and was reinforced by steel fibers in order to be prevented the total collapse separation because of tensile failure. Furthermore, an intact concrete beam specimen was surveyed (Figure 3A) for the obtaining of a control undamaged state beam dynamic response.

Concrete specimens were forced to vibration by exploiting a stinger striking shaker actuator driven by sinusoidal waveform with excitation frequency equal to 150 Hz. The direction of actuation force was decided to be parallel to beams' axis in order for propagation direction of generated mechanical waves to be perpendicular to cracks plane. Velocity signal acquisition was performed on a monitoring grid of 49 points (Figure 4) with sampling frequency FS = 7.85 kHz. The PSV-500H LSV equipment, although it performs acquisition procedure in time domain, returns only the Fourier response spectra of measured signatures that in the present case were calculated for $N = 400$ frequency points. Ambient light conditions were also an aspect that was investigated as it affects the level of noise and hence quality of measurements. It was concluded that for the specific monitoring situation, no essential influence was there by ambient light conditions. Finally, CSV CV_r^{sim} (Equation (4)) was calculated in a range of frequencies between 100 and 1200 Hz. This frequency range was resulted because although excitation signal comprised a single frequency equal to 150 Hz, the result waveform that propagated inside concrete mass was a multi-frequency signal composed by the several higher harmonics of initial frequency, namely, 300, 450, 600, 900, and 1200 Hz.

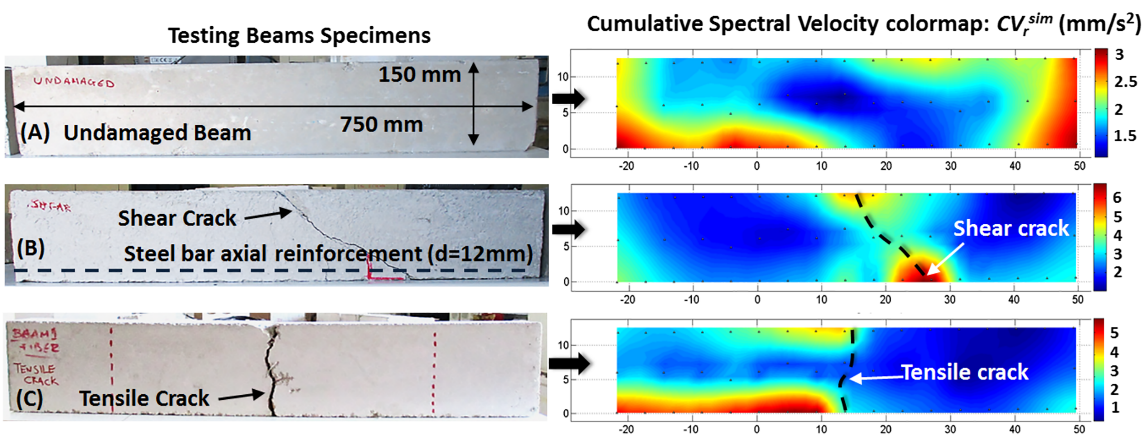

FIGURE 3 Beam specimens and respective cumulative spectral belocity colormaps CVr^{sim} for different types of beam damage state: (A) undamaged beam, (B) shear crack, and (C) tensile crack

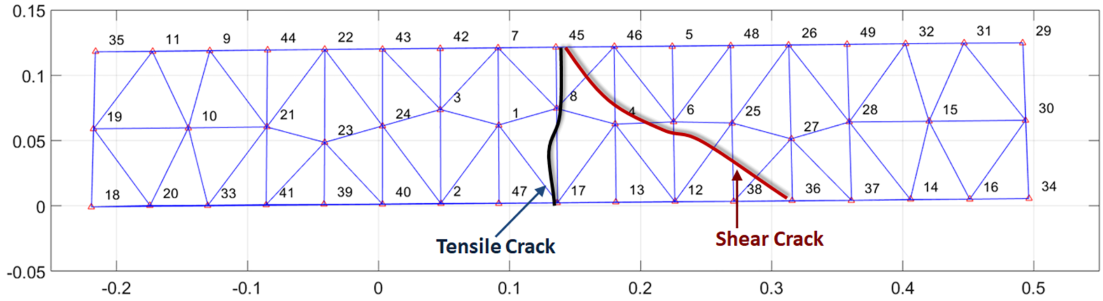

FIGURE 4 Mesh of the PSV-500H monitoring and kriging 2D regression points that applied in all damage cases

Figure 3 shows both concrete specimens that were surveyed by LSV and the spatial distribution of CSV. Cumulative velocity maps have been derived by application ordinary kriging regression to the set of 49 monitoring point, which formulates the scanning mesh of Figure 4. Comparing CV_r^{sim} maps of shear and tensile cracked beams, as they are shown to Figure 3B,C, with the map of undamaged one (Figure 3A), it can be stated that ordinary kriging regression attains to illustrate efficiently the changes beam dynamic response undergo because of damage existence.

The specific patterns of damage beams' dynamic response can be correlated both with crack position and the type of damage, providing additionally to structural inspection and damage identification. Shear crack influence is imprinted to cumulative velocity colormap (Figure 3B colormap) by giving a specific pattern of high CV_r^{sim} amplitude concentration at the regions of shear crack tips. This characteristic type of dynamic response pattern can be associated sufficiently with the existence of a shear crack. In case of tensile crack failure (Figure 3C), cumulative velocity distribution in beam regions on the left side of crack exhibits totally different features than the respective distribution in beam regions that are found on crack's right side (Figure 3C colormap). Taking into consideration that shaker actuator excitation force was applied on the left side of beam and parallel to its axis, it can be stated that tensile crack acts as a mechanical energy barrier regarding the propagating mechanical wave. This results a characteristic pattern of cracked beam dynamic response, which efficiently can be associated with a tensile crack existence.

5 | CONCLUSIONS

A novel implementation of LSV in concrete monitoring and damage diagnosis was presented. LSV technique combined with velocity signatures data normalization and kriging regression mapping is able to be employed efficiently in screening of concrete dynamic features by illustrating the vibration modes of concrete elements. Two types of damage beam were investigated, and their dynamic response patterns were compared against the dynamic response pattern of an undamaged concrete beam. From the analysis of experimental and post-processing data, results concluded that proposed methodology attains to produce high fidelity velocity maps that imprint reliably damage existence and their influence on concrete member dynamic response.

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CONFLICT OF INTEREST

Evangelos Liarakos and Providakis Costas declare that they have no conflict of interest.

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