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WAVE PROPAGATION BASED DAMAGE DETECTION IN STRUCTURAL ELEMENTS FOR CIVIL ENGINEERING STRUCTURES

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Abstract. Early damage detection in structures and systems plays a significant role in their overall life cycle since it enables early action towards preventing serious failure. The methods of structural health monitoring (SHM) provide reliable tools for early damage detection. Having information about the intact structure, SHM methods are developed that rely on discrepancy between the characteristics of the pristine and damaged structure. In this work particularly the structural elements constituting civil structures are considered from the point of view of further development, analysis, improvement, and implementation of the methods for damage detection in concrete and concrete-like materials. The methods addressed are based on the propagation of guided ultrasound waves through the structural elements under investigation, initiated by a piezoelectric driven source. Damage indices are defined based on the propagating wave characteristics, taking into consideration weakening of the wave energy in the presence of a damage. In addition, the methods are hybridized considering at the same time the signal time of flight in combination with interpolation of the damage index values over the discrete domains. Indication of the damage presence and its location is obtained through a corresponding superposition of the damage indices depending on the damage location, as well as on the number of excitation/receiver points on the considered structure. For two-dimensional propagation different study cases are considered in order to investigate detectability of the damage in dependence of the number of actuator/sensors points and their location. The feasibility of the approach is demonstrated in numerical experiment, whereas the required waveforms can be acquired in a similar manner from real experiments.

Key words: Damage detection, Wave propagation, Damage index, Time-frequency analysis, Concrete structures.

1 INTRODUCTION

The field of structural health monitoring (SHM) has been growing over the past years contributing to increasing reliability of structures through development of methods for damage detection. Particularly, nondestructive methods play significant role in early detection of structural damages since they provide an insight in the structural state without necessity to exert destructive impact on structures. On the other hand, such methods often require

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information about the intact states of a structure, which are used as a reference for comparison with the current state obtained through nondestructive evaluation. Different techniques can be used to acquire relevant states of structures under investigation; they may be based on acoustic emission [1], vibration analyses [2], laser scanning [3] or wave propagation [4]. The methods based on ultrasound wave propagation, owing to the frequency range of the propagating waves, aim at detection of irregularities of even extremely small dimensions. Piezoelectric transducers are well suited to initiate the wave propagation in structures under investigation in the frequency range of interest. This paper aims at presenting the results of the wave propagation-based method for damage detection and its localization in concrete elements trough analyses of the energy of waves propagating in intact and damaged specimens in combination with information on the wave travelling time till first obstacle or a boundary of a specimen. The method relies on assessment of damage indices obtained from the wave energy and time of flight (ToF) and is therefore regarded as a hybrid method.

2 WAVE PROPAGATION-BASED APPROACH FOR DAMAGE DETECTION IN CONCRETE ELEMENTS

The underlying idea behind the approach relies on signal processing of the ultrasound waves propagating through a structure to assess the energy content of corresponding waves. Passing by or through an obstacle, damage in a structure or any change of assumably (piecewise) homogeneous material properties, induces the dissipation of the wave energy resulting in change of the wave signature bearing the information on the energy content. The energy content builds an important constitutive part of parameters that indicate the damage existence. In this case such parameters are regarded as damage indices built upon the assessment of the wave energy. The method requires the wave energy content of both the pristine and damaged structural elements. An appropriate measure of the deviation between the wave energies for the intact and damaged state is defined by the damage index (DI). Damage indices are assessed for all predefined directions of the wave propagation. Those directions are determined by the placement of transducers used for wave initiation (actuators, emitters or sources) and transducers used as receivers of the arriving waves (also regarded as sensors). The proposed method can be implemented regardless of the source of waveforms: they could be obtained from the numerical simulation of the wave propagation or through experimental verification in laboratory environment. In this paper numerically generated waveforms were used.

3 IMPLEMETATION TO A CONCRETE STRUCTURAL ELEMENT

Damage detection and localization is performed on a square-shaped concrete element, with thickness ten times smaller than the in-plane dimensions of the element, allowing thus for consideration of 2-dimensional wave propagation. The damage of a circular shape is treated as a part consisting of material with different properties or a hole through the constant thickness of the element. Since in this case the thickness of the specimen is much smaller in comparison with other dimensions of the square-shaped specimen, a 2D problem is considered. Figure 1 shows the concrete specimen under investigation and its schematic representation [5, 6].

Numerical simulation is performed in Abaqus/Explicit software. The concrete plate is modelled using the homogenized material properties of concrete with velocity of longitudinal wave propagation of 3.592 m/s, elasticity modulus 30 GPa, Poisson's ratio 0.1, and density 2.377,30 kg/m^3 [5]. In addition, the meshing was performed considering the recommended size of the finite elements, namely 7-30 elements per wavelength, whereas the wavelength of the excitation waves directly correlates with the presumable damage size.

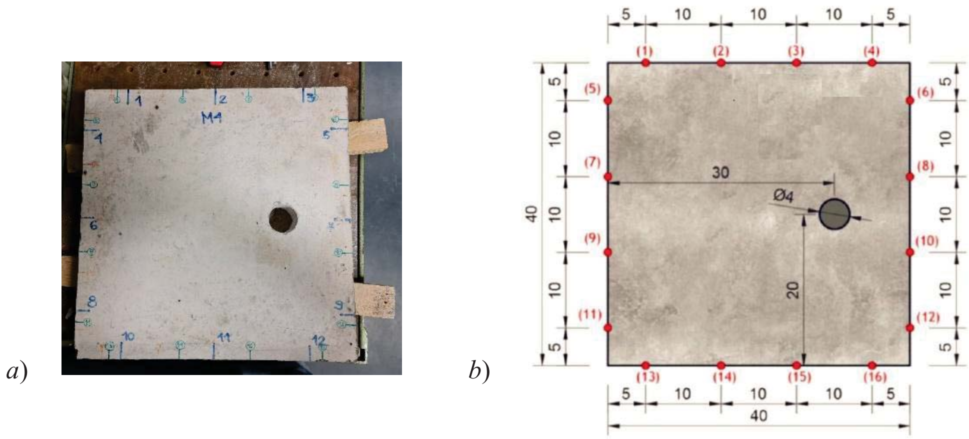

Figure 1: (*a*) Photo of the square-shaped concrete specimen and (*b*) its schematic (dimensions 40×40×4 [cm]) with actuator/sensor positions (enumerated red dots)

For the assessment of the wave energy for each actuator/sensor (AS) pair, the signal at receiver is evaluated in numerical simulation as response to the excitation wave (3,5 cycle hanning-windowed wavelet with center frequency of 100 kHz). The parameters of the excitation signal are primarily selected to comply with the measurement equipment used in laboratory experiment, where the piezoelectric transducers used for the excitation exhibit maximal magnitudes at designated center frequency of 100 kHz. The excitation signal in time domain and its frequency spectrum are represented in Figure 2.

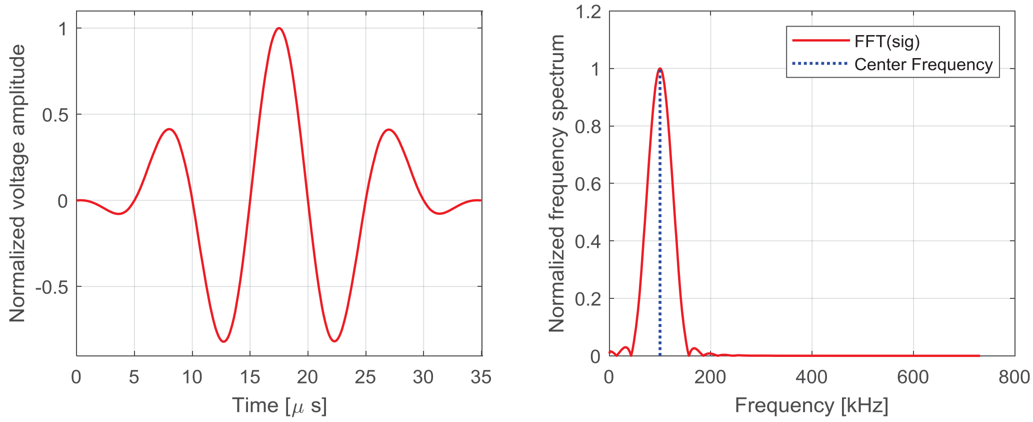

Figure 2: Excitation signal (*a*) and corresponding frequency-domain representation (*b*).

Further analyses rely on verified linearity between the force exerted by the source transducer and corresponding displacement at the mid-contact point between the transducer and the specimen, both expressed in terms of corresponding electric voltage, as shown in Figure 3. This reasoning justifies opting-out the detailed numerical modelling of the piezoelectric transducers and substituting their influence by corresponding degree of freedom at predefined single-point location. This in turn enables considerable computational savings in numerical simulation of the wave propagation.

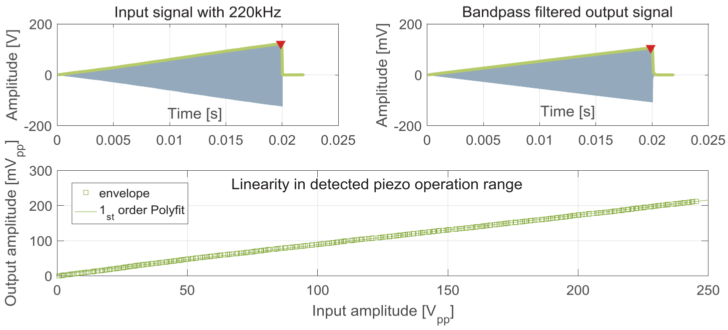

Figure 3: Assessment of the input/output linearity

3.1 Energy-based damage index for damage detection

A wavelet passed through actuator propagates through the specimen and captured by the receiver replicates with certain delay the initial waveform in the first arriving packet to an extent which depends on the presence or neighborhood of the damage in the line of the corresponding AS-path. Damage index on an AS-direction in its basic form is defined as relative deviation of the energy in damaged state from the energy in intact state:

$$DI \cong \sqrt{\frac{(E_d - E_h)^2}{E_h^2}} \tag{1}$$

Basically, the energy of the signal can be determined from the time-series of data acquired in numerical or laboratory experiment. For high frequency analyses in the ultrasound bandwidth the calculation of the wave energy is related with high computational effort if the energy is determined directly from the waveform. In this study wavelet decomposition of the receiver signal in approximation and detail is performed at multiple levels to determine the wave energy approximation in an efficient way. The DI is then calculated from the resulting energy from each decomposition level.

3.2 Signal analysis

Pure visual inspection of the wave forms in time domain from different AS paths cannot provide precise information on the exact moment of the first deviation occurrence between the waveforms of the damaged and intact structure. Further analyses incorporating the wavelet transform can provide valuable information on the signal time/frequency/magnitude dependence as well as pronounced visualization of the deviation occurrence. Such an inspection enables by specifying the threshold magnitude as a measure of the occurrence to precisely identify the moment of significant energy change between the intact and the damaged state. Selected results of such analysis are presented in subsequent figures. Presented scalograms are obtained by implementation of the wavelet transform to waveforms of the receivers. For comparison two paths are selected: a path passing directly through the damage, from actuator A_5 to sensor S_{10} (Figure 4), and a path far away from the damage, from actuator A_5 to sensor S_{13} (Figure 5).

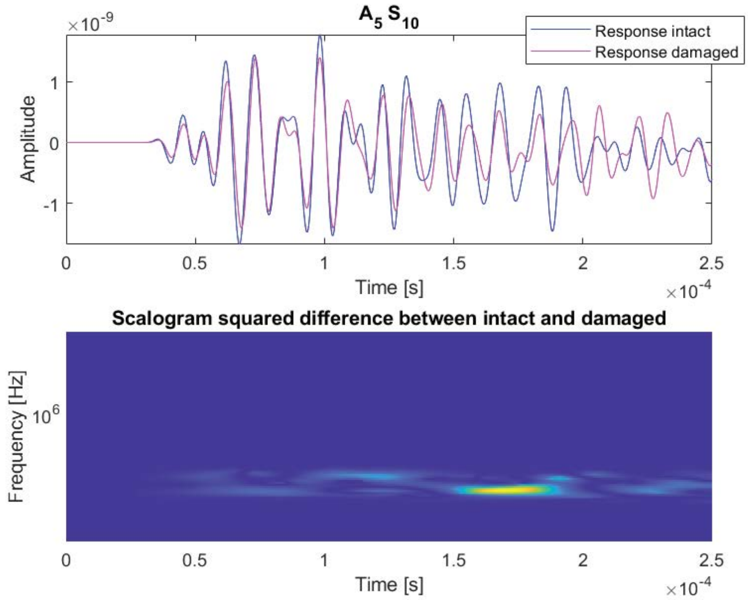

Figure 4: Path through the damaged region, from Actuator A_5 to sensor S_{10}:
up – waveforms, down – scalogram

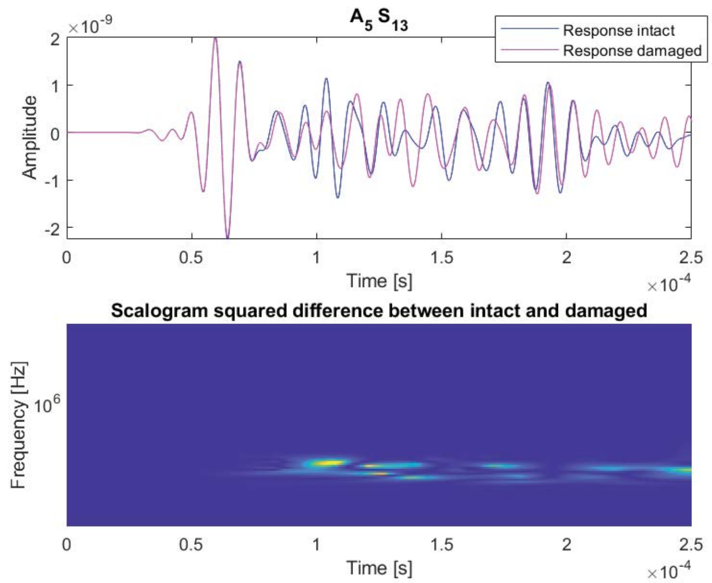

Figure 5: Path far away from the damaged region, from Actuator A_5 to sensor S_{13}:
up – waveforms, down – scalogram

The scalograms clearly show that the energy deviation between the damaged and the intact case starts earlier on the path through the damage. In addition, the highest energy difference, hill regions in the plots, occur at the wave packets corresponding to reflection for both presented paths. In the path far away from the damage (Figure 5) the energy difference occurrence is visible after 0.5 s, whereas in the damaged case it is already visible before 0.5s. Scalogram is presented in terms of the squared energy difference to emphasize the regions with higher difference.

3.4 Consideration of the Time-of-Flight

The time-of-flight is implemented in the process of localizing the damage by considering only the actuator-sensor pairs that exhibit a difference in the ToF between the intact and damage case of the concrete plate. These paths are then considered for the localization of the damage using the hybrid method that we developed, which relies on the interpolation between the considered AS pairs. The signals of the intact case are further post-processed in such a way that their amplitudes between the ToF corresponding to the intact case and the corresponding ToF of the signal on the same path at the damaged case are set to zero. This was considered to reduce the amplitude change of the signals in the intact case after their arrival at the sensor, thus, controlling the change of energy between the intact case and the damaged case after arrival at each sensor.

3.5 Results of the damage detection

Implementing described approach along with the investigation of the influence of the number and position of actuators and sensors, the damage existence could be confirmed and localized, as depicted in Figure 7. In the first step, a relatively rough AS network was selected, with four transducers at each side of the square specimen. After indication of the region of possible damage, the number of transducers is increased in relation with this region as shown in Figure 7. The refinement of the AS network could provide higher precision of the damage localization. As further parameter, the threshold filter value is introduced and applied on the interpolated DI values relative to the maximum value of DI in the specimen. Thus, the DI values are first normalized and then the threshold (percentage value of it) is considered to specify the damage area. It was gradually increased (see legend of Figure 7) to facilitate for the increased precision of the damage localization. The color scale on the right-hand side of the figure represents the interpolated damage index values scaled from 0 (no damage) to 1 (maximal damage).

4 CONCLUSIONS

The results of the damage detection and localization in concrete 2D elements are presented in this paper implementing a hybrid approach based on ultrasound wave propagation. The methods addressed are based on the propagation of guided ultrasound waves through the structural elements under investigation, initiated by a piezoelectric driven source. Damage index is defined based on the propagating wave characteristics, taking into consideration weakening of the wave energy in the presence of a damage. In addition, a hybrid approach is considered, which combines the signal time of flight with interpolation of the damage index values over the discrete domains. Indication of the damage presence and its location is obtained through corresponding superposition of the damage indices depending on the damage location, as well as on the number of excitation/receiver points on the considered structure. Presented case study shows a good evaluation of the damage presence and location.

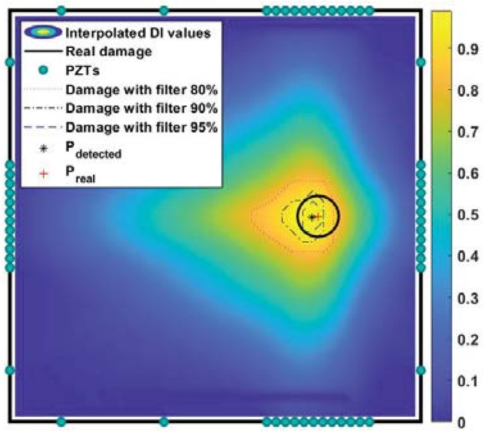

Figure 7: Damage localization with ten additional sensing points in the region identified as region of damage occurrence in the first damage localization step with 12 sensing points.

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