Energy Based Ultrasonic Techniques for Early-stage Damage Detection in Concrete Structures

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ABSTRACT

During the service life, concrete structures undergo several adversities that lead to weakening in concrete and results in crack initiation. At initial stage of damage, breathing /clapping effect prevails inside the material. It results in additional nonlinearity, called as contact acoustic nonlinearity (CAN) in the structure which is often subsumed due to the material nonlinearity and leads to unidentified progression of damage inside structure. In the present study, ultrasonic investigations have been carried out to detect the flexural cracks in a scaled model of a reinforced concrete (RC) girder-deck system under four-point bending where the damage stages can be categorized as, undamaged (Stage 0), crack initiation (Stage I), crack propagation (Stage II), and severe damage (Stage III). Data acquired from ultrasonic actuation-sensing at different damage stages are processed in time-frequency domain and frequency domain using energy based ultrasonic parameters, such as, wavelet packet energy and spectral energy distribution. Further, a new energy based nonlinear acoustic parameter (ENAP) is introduced that works on the harmonic phenomenon induced by the breathing cracks. The proposed energy based methods (especially nonlinear methods) are found to be very efficient for detecting all the damage levels successfully.

INTRODUCTION

Concrete structures, especially, Reinforced Concrete (RC) bridges face several critical damage scenarios due to excessive traffic load, fatigue cycling, extreme environmental variation, ageing and most importantly, poor design and low maintenances etc. [1]. Now-a-days, damage detection and performance evaluation of bridge structures are of high concern, hence, it has become an emerging field of research for Structural Health Monitoring (SHM) community. In case of heterogeneous construction material, like concrete, complexity starts to appear from very beginning, i.e. from the material microstructure stage. Due to difference in properties of each individual element (aggregates, sand, binder cement, water), concrete becomes highly heterogeneous in nature. Additionally, the internal aggregate- matrix transition zones (ITZs) play a crucial role for defining the material properties. Being a soft phase, interfacial transition zones (ITZ) get primarily affected and most of the damages (micro cracks, alkali-silicate reaction induced damage etc.) start to originate here [2].

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Hence, an undamaged concrete structure may possess several internal micro damages (that are distributed in nature) before application of any mechanical loading. Once the loading starts, the distributed micro cracks grow, coalesce together and lead to macro damages (see Figure 1). From past several years, few traditional destructive testing methods (DT) [3] and several non-destructive methods (NDT) have gained attention as efficient health monitoring methods [4]. Among them, specific advantages and feasibility of ultrasonic methods are described in [5,6]. Linear ultrasonic techniques (wave velocity, attenuation) have shown successful application in most of the field investigations [7,8]. However, because of few limitations [9], linear ultrasonic methods may not work efficiently, particularly, for early crack detection [10], minor interfacial flaw detection in composite system [9] etc. On the other hand, advanced nonlinear ultrasonic techniques show better efficiency and sensitivity over the linear methods. Wave modulation techniques [11,12], resonant ultrasound methods [13,14], time reversal methods [15,16], super harmonic generations [17,18] are the most popular nonlinear ultrasonic methods. In presence of different kind of damages, the most salient feature is the generation of noticeable peaks/ harmonics (super/sub) in the frequency spectrum of the response signal. It is also to be noted that, several small peaks are generated on both sides of the fundamental peak (sideband region) and throughout the frequency window [10]. Recently, Kundu and his research group [9,10,19-22] have established a powerful nonlinear ultrasonic method, called as SPC-I and gradually improvising the technique for higher sensitivity and wide range of applications. In this study, experimental investigations are performed on RC girder-deck system for identifying the flexural cracks under progressively increasing load levels that can be categorized as, (Stage I)- crack initiation, (Stage II)- crack propagation, (Stage III)- severe damage. Energy based ultrasonic techniques (Linear/ Nonlinear) are followed in signal processing stage. Linear wavelet energy (WPE) infers the energy transmissibility of the signal in presence of damage, whereas, Sideband Energy Ratio (SER) and Energy based Nonlinear Acoustic Parameter (ENAP) works on the nonlinear peak growth in the frequency spectra. Sometimes, harmonics may not appear (or may appear in very feeble form that can be hardly noticed) depending on several conditions, such as voltage limitation, cracking pattern (in terms of crack density, width etc.). In such cases, the novel ENAP method (based on harmonic energy) can be a promising technique for identifying and characterising the damage. The experimental procedures followed by the results and observation are explained in the following subsections.

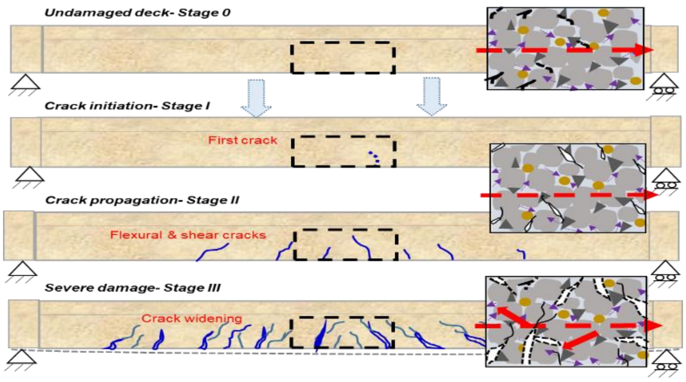


Figure 1. Schematic diagram of a RC deck showing different stages of damage propagation with successive loading.

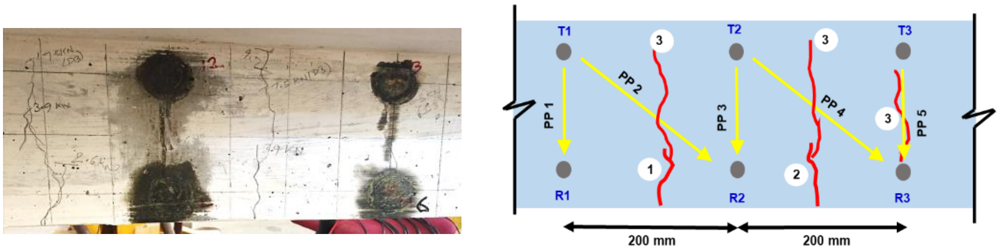
EXPERIMENTAL INVESTIGATIONS

Specimen Details and Loading Procedure

Experimental investigation is conducted on a girder-slab system of an RC bridge specimen of 4.5 m length. 2 no. 12 dia (bottom bar) and 2 no. 8 dia (hanger) are used as longitudinal reinforcement of the beam and cube strength is found as 43 MPa. A servo-hydraulic actuator (25 tonne capacity) is used to induce four-point bending on the deck system. It is targeted to identify the damage mechanism in three loading stages- Stage I-that induces the first visible crack (2.6 kN), Stage II- that initiates crack propagation and widening (5 kN), Stage III- that induces formation of several number of macro cracks (width ~0.2 mm) enhancing the damage severity (10.6 kN, i.e., 40% of ultimate load). Once the external loading stabilises in each damage level, the ultrasonic testing is followed up.

Instrumentation and Ultrasonic Testing

The present study is focused to monitor flexural damages of the concrete beam and its propagation with progressive loading. In view of this, a pure flexural zone is selected for the ultrasonic data acquisition and three sensor positions are marked at equidistance (in 200 mm gap) (see Figure 2). Here, three wave propagation paths are considered at straight direction- T1-R1 (PP1), T2-R2 (PP3), T3-R3 (PP5) and two wave propagation paths are considered at diagonal direction- T1-R2 (PP2), T2-R3 (PP4). Point to be noted, that the first crack has appeared between T1-R1 and T2-R2. Several strain gauges are attached for monitoring the load levels in concrete surface as well as in reinforcing bars. The ultrasonic measurement is carried out that involves- waveform generator, two channel isolated amplifier, ultrasonic transducers (23 mm diameter- central frequency of 1 MHz), a digital oscilloscope and data acquisition systems.



(a) (b)

Figure 2. (a) crack generation on the flexural zone of RC bridge; (b) schematic representation showing the transmitter-receiver locations, and appearance of cracks in sequence (where 1,2,3 denotes successive load levels).

RESULT

Hanning type tone burst pulse of 5- cycle with central frequency of 50 kHz is transmitted along five of the propagation paths with amplified amplitude of 50 V_{pp} and received at three of the sensors (R1, R2, R3) with sampling frequency of 1 MHz. The received signal of 1 ms length is analysed through different energy based techniques as mentioned in the following sections and the corresponding sensitivities are calculated.

Energy Based Linear Ultrasonic Method- WPE

Wavelet packet analysis (WPA) is a time-frequency domain approach that involves multiple iterations for successive decomposition of wavelet packets [23,24]. WPA splits the waveform in both approximate and detailed coefficients (i.e. both low-pass and high pass filter coefficients). Hence, it precisely extracts damage sensitive features of high frequency components of the signal (details in [9]). In the present case, WPA analysis is performed upto 3rd level using Daubechies type 2 wavelet. Basically, the process of energy transmission gets affected because of several structural damages, including cracks or other bond-slip issues. Hence, the energy content of the signal starts to retard with damage progression. The reduction in energy loss can be detected w.r.t the initial undamaged energy state by using linear Wavelet Packet Energy (WPE) parameter (see Equation 1)

$$WPE = \left| \frac{Energy\ difference\ between\ undamaged\ and\ damaged\ state}{Energy\ of\ undamaged\ stage} \right| \quad (1)$$

The increasing trend of WPE parameter along PP1-PP5 (see Figure 3) with the successive load levels suggests, the method is able to detect the loss of energy (due to formation of micro cracks). A drop can be found for PP4 from Stage II (i.e. 5 kN). At last stage of loading (Stage-III), major crack has been formed and propagated between the transmitter position T2-R2 & T3-R3 and also, between T3-R3 (see Figure 2). Probably, the method WPE fails to assess the damage propagation once a huge change in waveform takes place in presence of several number major cracks. Likewise, the lesser sensitivity of the WPE parameter is also visible for PP5. Because, the ultrasonic wave is directly interacting with the major crack between T3 and R3 probe locations. Therefore, it can be concluded that, energy based parameter using wavelet packet analysis, can effectively monitor the load induced damages (with an initial sensitivity of 10-30%) before any medium to major damage (or crack) takes place in the system.

Energy Based Nonlinear Ultrasonic Method- SER

From the FFT graphs (see Figure 4), it can be observed that, even in undamaged stage (Stage 0), several major/minor peaks are visible around the fundamental peak and these peaks are growing (increasing in number and width) with the successive loading stages. This happens especially for concrete like material because of multiple scattering effects that interact and modulate the main pulse. The ratio of the energy content in the surrounding sideband peaks (both side of the main peak) to the energy content at the maximum fundamental peak is termed as SER and can be used as a nonlinear ultrasonic parameter for further signal analysis (see Equation 2).

$$SER = \frac{Total\ sideband\ energy}{Fundamental\ energy} \quad (2)$$

The nonlinear parameter based on SER increases with loading (see Figure 5). The ultrasonic wave along the propagation path PP1 and PP3 don’t interact with the cracks directly, therefore, they have shown minimum sensitivities. At last stage (10.6 kN), several cracks might have formed in these locations which are not readily noticed from surface, hence it shows increased values at last stage. Whereas, the wave path PP5 is much affected by the cracks and its nonlinearity content is reflected in the graph. On the other hand, the waves along PP2, PP4 i.e. two diagonal propagation paths are directly interacting with the micro/ macro cracks from the initial level of loading, and hence, their performance is much better than the previous two straight propagation paths (PP1, PP3). The damage induced nonlinearity effect is higher for PP4 (than PP2) as it faces higher crack densities in each damage level (mainly at last two stages).

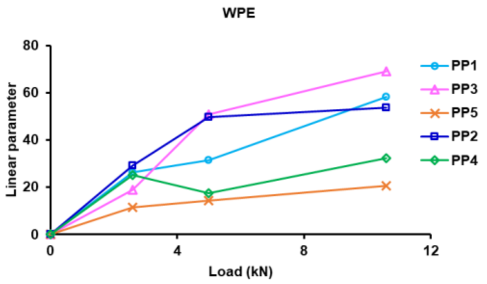
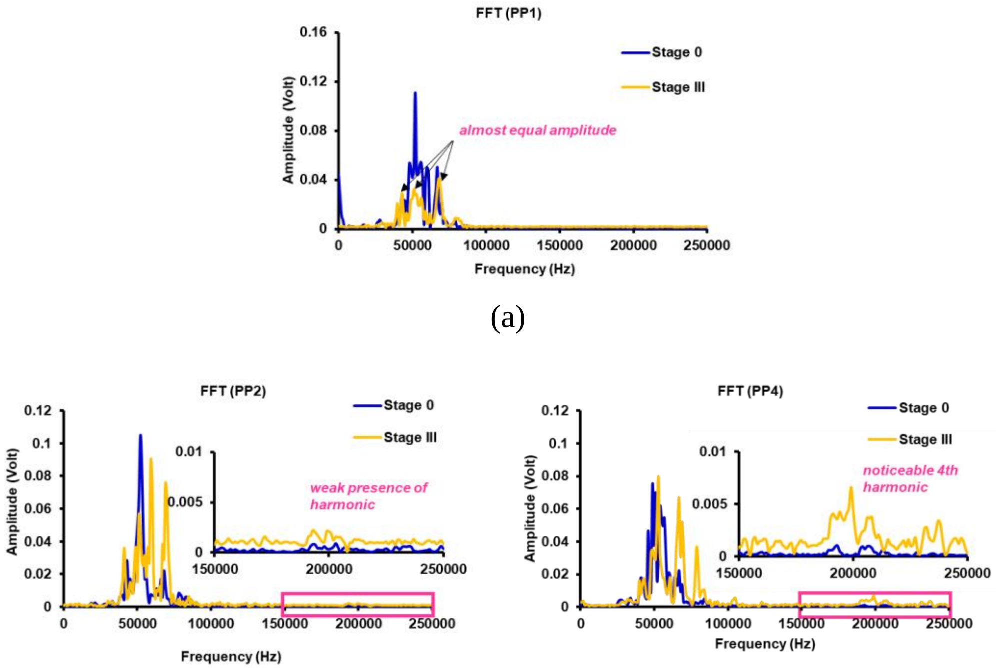


Figure 3. Energy based linear WPE method along PP1 to PP5.



(a)

(b)

(c)

Figure 4. FFT for propagation paths: PP1 (direct), PP2 & PP4 (diagonal).

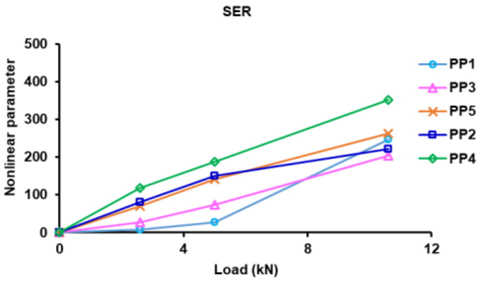


Figure 5. Energy based nonlinear SER method along PP1 to PP5.

Energy Based Nonlinear Ultrasonic Method- ENAP

In extension to the previous observations, it can also be noticed from the graphs that, few small peaks are distinguishably visible (though having lesser amplitude) in the harmonic frequency position (mainly at 4th order). The existence of that harmonic peak starts to gradually build-up in the next damage stages and forms very feeble, still, noticeable presence in the subsequent levels. Here, the FFT of two stages are shown (Stage 0 and Stage I), where the harmonic is remarkably visible at the 4th order position for the last load stage. An energy based nonlinear acoustic parameter ENAP is derived using the acoustic nonlinear information, where the energy of the 4th order harmonic frequency band (of certain width) is measured w.r.t the energy at the fundamental frequency band (see Equation 3).

$$ENAP = \frac{Energy\ at\ 4th\ harmonic\ frequency\ band}{Fundamental\ energy} \tag{3}$$

This phenomenon is specially noticed for two propagation paths (PP2, PP4), hence, the nonlinear ENAP method is applied to these two particular response signals (T2-R2 and T3-R3). As, the waves along these two paths are interacting directly with the micro/macro cracks, these are able to capture the breathing effect/ clapping of the cracks and efficiently exhibit the nonlinear effects in their frequency spectrum. Both the plots present that, the ENAP is successfully monitoring all of the damage levels. In case of PP4, the parameter is showing maximum value (450% at last stage), as it faces higher crack density along its propagation path. The compressional part of the ultrasonic waves can go through the cracks, capture the breathing effect during the load applications and generate the harmonics as a nonlinear signature (CAN).

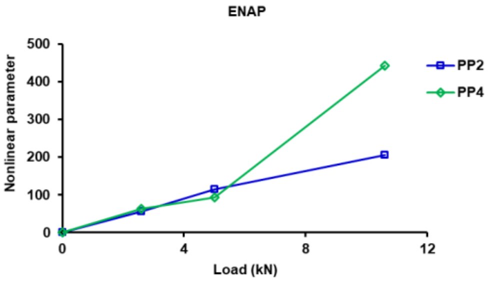


Figure 6. Energy based nonlinear ENAP method along PP2 and PP4.

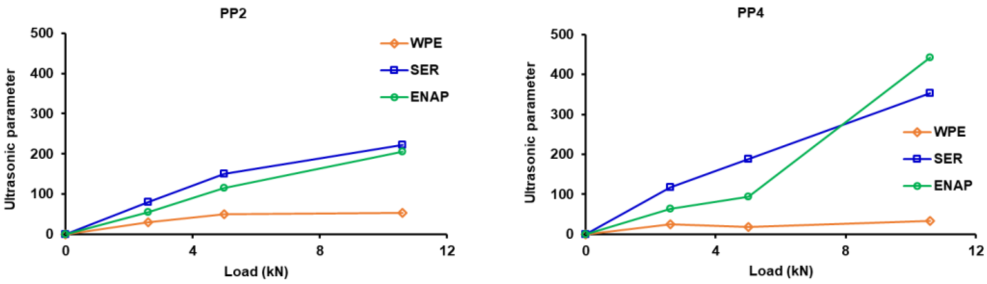


Figure 7. Comparative study on energy based ultrasonic methods along PP2, PP4.

OBSERVATION AND CONCLUSION

The present experimental study has been conducted to effectively monitor the flexural cracks in RC bridge girder system using ultrasonic wave propagation under three specific damage conditions. For that purpose, energy based ultrasonic parameters are employed using time-frequency domain (WPE) and frequency domain analysis (SER, ENAP). The critical observation from this experimental study suggests, 1) in case of distributed damage/ cracks (e.g. flexural/ shear cracks in any beam structure), diagonal actuation-sensing configuration is much effective that can interact with higher number of cracks and bring more accurate damage induced nonlinear features; 2) Energy based linear WPE has shown good capability in detecting damage levels from initial to medium damage condition with sensitivity of 30-50%. It can overcome the limitation of traditional linear methods which shows inefficiencies in early stages. However, this method may show less sensitivity at extreme damaged case, where high modulation and extreme distortion affect the waveform. 3) Energy based nonlinear SER, ENAP method have shown almost similar sensitivity and it can detect breathing effect of micro cracks more efficiently using the nonlinear signature of frequency spectrum. SER method is applicable for all of the propagation paths with sensitivity of 120-350%. ENAP has the capability of identifying crack induced CAN in presence of harmonic peaks (even under insignificant presence) with sensitivity of 60-450%. Therefore, apart from the well-established amplitude dependent methods, energy based methods are highly efficient for detecting different level of load induced damages and can be applied for SHM (for attaining better sustainability and reliability) of in-situ structures.

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