Vibration based Condition Assessment of Deteriorated Reinforced Concrete

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ABSTRACT: The commonly used electrical resistivity based methods are beneficial to estimate the mass loss of the reinforcement. However, it is also possible to estimate overall deterioration caused by corrosion in the reinforced concrete (RC) elements by using vibration based methods. In the conventional vibration tests, the condition assessment is mostly based on monitoring the changes in the modal frequencies, which may not provide an objective interpretation in all cases. Instead, monitoring the nonlinear behavior in the dynamic response of the structural elements may serve better for the purpose of assessment of structural integrity. Herein, a diagnostic feature which represents the significance of non-linearity in the response vibration of the structural elements is discussed. This feature quantifies the severity of damage by measuring the magnitudes of higher harmonics of fundamental modes existing due to the damage in the element. In this paper, an adaptive higher order spectral analysis method is demonstrated on the simulated data in order to detect and quantify the non-linearity, and hence the structural damage. This study is planned to be extended to experimental works on the lab-scale RC columns with varying corrosion conditions.

1 INTRODUCTION

Estimation of the severity of corrosion in the reinforced concrete (RC) structures is typically performed using electrical resistivity method, so that the mass loss of steel reinforcement, and hence the remaining diameter size of rebars can be determined (ASTM C876-15). Whereas, the deterioration in the concrete as a by-product of the corrosion is not concerned until it appears as surface breaking cracks or in the form of delamination. And when such deterioration in the concrete is observed, its condition is assessed mostly by the means of ultrasonic methods which are capable of estimating the crack/damage location and size (ASTM C597-16; ASTM C1383-15; Kirlangic et al. 2016). Instead of considering the assessment of the reinforcement and the concrete separately, an overall approach to diagnose the structural health of a RC element as a whole composite material using vibration-based methods is deemed time effective.

In conventional vibration based condition assessment the main diagnostic features that are investigated are the modal frequencies and the mode shapes to assess the overall structural integrity. Since any deterioration occurred in the structure alters these structural properties, the changes in these features are monitored to evaluate the overall condition of the structure in service. However, in reality it is not easy to make an objective and meaningful interpretation of the small changes in the structure's natural modes (Farrar et al. 2004). In addition, the properties of the healthy structure are needed as a priori to be compared to the current state of the structure. Instead of monitoring the small shifts in the fundamental frequencies of the structure, observing the higher harmonics of the fundamental modes can provide more accurate diagnosis.

Detecting the existence of higher harmonics for the condition monitoring of the machinery systems has been a long practice. Since any structural damage introduces nonlinearity in the dynamics of the system, the damage can be traced in the vibration signals. Same principle applies for the damaged structures where the tensional stiffness differs from the compressional one causing a bi-linear behavior (direction dependent stiffness) within the oscillation of the structure. The degree of this nonlinearity, and thus the extent of the damage, can be quantified by performing higher order spectral analysis on the vibration signals recorded on the structure (Fackrell JW et al. 1995; Collis WB et al. 1998). Higher order spectra (HOS) is defined as the Fourier transforms of higher order cumulants of a random process (Chadran et al. 1994). The second order spectrum is known as the traditional power spectrum, whereas the third order is called bispectrum. Among these two, the bispectrum is of particular interest because it reveals the phase coupled harmonics of the vibration frequencies, which is a direct measure of the magnitude of the existing nonlinearity in the system. The HOS analysis, and particularly bispectrum, is mostly applied for monitoring the mechanical systems, such as engines, turbine blades, gearboxes, etc. (Jeffries et al. 1998; Parker et al. 2000; Rivola et al. 1998); whereas the implementation of this approach for the condition assessment of the reinforced concrete structures is not exploited satisfactorily yet.

Herein study demonstrates a preliminary numerical work which aims to assess the corrosion-induced deterioration in the structural reinforced concrete elements using the bicoherence technique. For this purpose, first the simulated vibration signals are generated based on a basic bi-linear model, which represents the deteriorated elements, and then the diagnostic feature is extracted from the vibration signals utilizing the bispectral analysis. The effectiveness of the proposed method is presented by comparing the features obtained from the undamaged and the damaged models.

2 SIGNAL PROCESSING

Extraction of the diagnostic features from the vibration signals can be realized by utilizing various signal processing techniques, such as frequency, time-frequency and wavelet analyses. Depending on the excitation type (stationary or non-stationary) used in the vibration tests, the data processing technique is adapted as to suit the vibration signals, so that the most reliable diagnostic feature can be obtained. Hereby, the bispectral analysis is modified by incorporating wavelet transform, instead of the conventional Fourier transform. The wavelet transform is an integral transform of a signal with a selected mother wavelet that can be scaled and shifted as required using the following expression:

$$W_{\psi}(a,t) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t') \Psi^{*}\left(\frac{t'-t}{a}\right) dt' \tag{1}$$

where a is the scale parameter, t is the time shift, $x(t')$ is the time signal, and Ψ^{*} denotes the complex conjugate of the mother wavelet. The main reason of using the wavelet transform is that it suits the vibration response upon the impulse excitation. The wavelet transform provides the flexibility of choosing a wavelet function suiting the transient vibration signals better than the kernel of the conventional Fourier transform.

Damage diagnosis is performed with the third order wavelet based spectral analysis which provides the wavelet bispectrum indicating the phase couplings of the resonance harmonics. The Wavelet Bispectrum is defined as (Collis et al. 1998):

$$B_W = \left(\frac{1}{T}\int_{t-T/2}^{t+T/2} W_\psi(a_1,\tau)W_\psi(a_2,\tau)W_\psi(a_3,\tau)\,d\tau\right) \tag{2}$$

where T is the time interval at time t.Scale parameters hold the relationship of:

$$\frac{1}{a_3} = \frac{1}{a_1} + \frac{1}{a_2} \tag{3}$$

The normalized bispectrum is called bicoherence, b, which is given as (Collis et al. 1998):

$$b_W = \frac{B_W}{\sqrt{\left|W_\psi(a_1,\tau)W_\psi(a_2,\tau)\right|^2 \left|W_\psi(a_3,\tau)\right|^2}} \tag{4}$$

As it is a normalized quantity, the bicoherence has a value between zero and one. Because the magnitudes of the higher harmonics increase with the nonlinearity, a higher b value is expected as the damage severity increases.

3 THE SIMULATION OF DAMAGED RC ELEMENTS: BI-LINEAR MODEL

Damage in materials cause reduction in the cross-section of the elements, and does in structural stiffness. Under dynamic loading, opening and closing of the cracks can be simulated by the bi-linear model (Rivolaet al. 1998). The bi-linear oscillator, shown in Figure 1 introduces bi-linearity in the equation of motions with direction depended parameters as:

$$\begin{aligned} \ddot{u} + 2\zeta\omega_1\dot{u} + \omega_1^2 u &= F(t) \quad u \geq 0 \\ \ddot{u} + 2\zeta\omega_2\dot{u} + \omega_2^2 u &= F(t) \quad u < 0 \end{aligned} \tag{5}$$

where u is the displacement, the angular frequency $\omega = \sqrt{k/m}$, and the damping ratio $\zeta = c/2\sqrt{km}$; m, k, and c denote mass, stiffness and viscous damping of the element respectively. The period T_0 and frequency ω_0 of the bi-linear model are therefore, given by:

$$\omega_0 = \frac{2\pi}{T_0} = \frac{2\omega_1\omega_2}{\omega_1 + \omega_2} \tag{6}$$

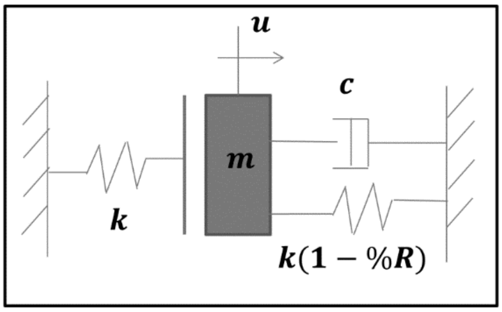

Figure 1. The bi-linear model.

Any given mass of the structural element, m is equal to ρAL, where ρ, A, and L are the density of the material, the element's cross-sectional area and length respectively. And finally, R is the stiffness reduction in the tensional direction due to the cracking.

The bi-linear model is created as to simulate the first bending mode of a 7-meter long 20 by 20 cm^2column. For typical structural concrete, given the density $\rho =$ 2400 kg/m^3, the elasticity modulus $E =$ 30 GPa, and the damping ratio $\zeta =$ 5%, the fundamental resonance frequency of the first bending mode is calculated as81 Hz. The damage in the RC column is introduced into the model by reducing the stiffness in tension by a certain percent, while keeping it same for the compressional direction. The first bending mode of the undamaged column and five damaged columns with 5%, 10%, 15%, 20%, and 25% stiffness reduction in tensional direction are modeled.

The equation couple given in Eq. 6 is formulated in the state-space model and solved under the impulse excitation by numerical integration in time domain. The impulse excitation in time and frequency domains are both shown in Figure 2. The frequency range of the impulse excitation is chosen in accordance with the resonance frequency of the intact column. The simulated signals for the undamaged and 25% damaged elements are shown in Figure 3. The existence of the damage is detectable on the power spectrum given in Figure 3, where the missing higher harmonic in the spectrum for the undamaged column become apparent for the damaged one.

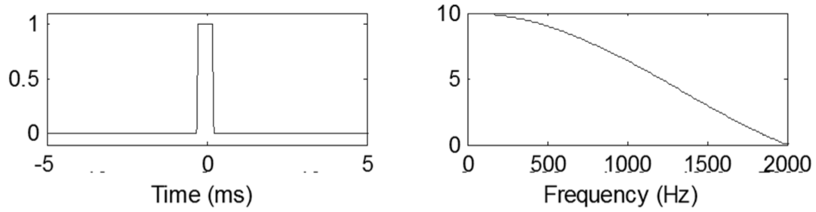

Figure 2: Impulse excitation in time and frequency domains.

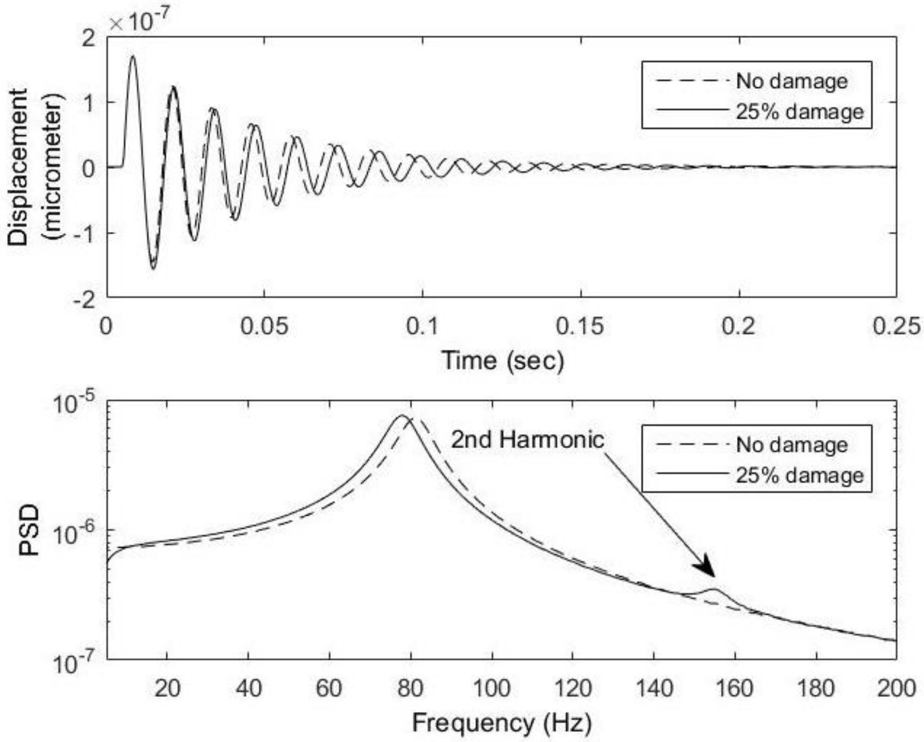

Figure 3: The simulated pile vibrations.

4 THE METHODOLOGY FOR DIAGNOSIS

The proposed diagnostic methodology includes the following steps:

- The resonance and its higher harmonics in the vibration time history is determined in the power spectral density (Figure 3).
- The Morlet function is chosen as the wavelet function, of which central frequency is set in accordance with the fundamental frequency of the vibration signal.
- The wavelet transform is performed for each harmonics separately, the central frequency of the wavelet function is scaled up in accordance with the higher harmonics.
- The bicoherence value is calculated as given in Eqs. 2&4 by using the wavelet magnitudes obtained for each harmonics. The value of bicoherence represents the coherence between the fundamental vibration frequency and its second harmonic. Stronger the higher harmonics, the larger values of bicoherence is attained.
- The bicoherence calculation is repeated 100 times after adding white Gaussian noise to the original signals in order to create a data set. The histograms given in Figure 4, display the bicoherence values obtained from the undamaged and 25% damaged RC columns, where the separation of the damaged features from the undamaged ones is apparent.
- The effectiveness of the diagnosis is quantified with the Fisher's linear discriminant analysis as:

$$FC = \frac{|\mu_1 - \mu_2|^2}{{\sigma_1}^2 + {\sigma_2}^2} \tag{7}$$

where μ and σ^2 are mean and variance of the diagnostic bicoherence features. The parameter FC, the Fisher's criterion, indicates the degree of separation between the data sets of undamaged and damaged features, which is found as 99.5 for the 25% damaged column. The overall correlation of the Fisher's criterion with respect to the damage percent is plotted in Figure 5.

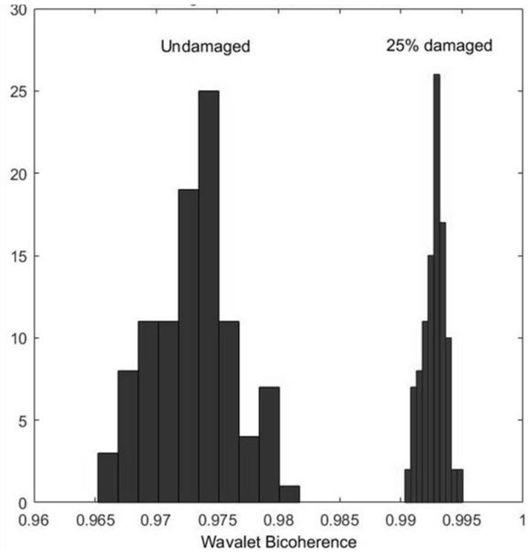

Figure 4: Histogram of the bicoherence.

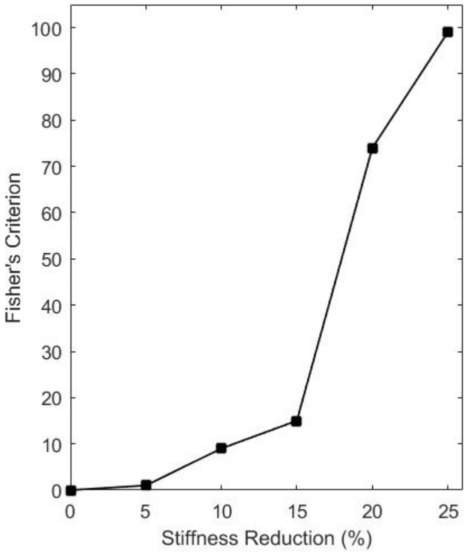

Figure 5: FC with respect to damage.

5 CONCLUSIONS AND FUTURE STUDY

The diagnostic methodology based on the wavelet transform and the bicoherence technique is introduced and the results of the implementation on the simulated signals are demonstrated. The diagnostic features obtained from the undamaged and the damaged models reveal clear separation indicating the successful identification of the damaged element. The preliminary work presented hereby is planned to be proceeded by the experimental works to validate the diagnostic methodology. The planned tests will be conducted on the laboratory-scale reinforced concrete corroded at a certain level as shown in Figure 6. The vibration tests will be executed with an impact hammer along with the test set-up illustrated in Figure 7. By the completion of this experimental research work, it is aimed to develop the optimum test set-up and configuration along with the diagnostic software that will be capable of assessing the overall reduction in stiffness of the corroded RC elements.

Figure 6: The lab-scale RC columns.

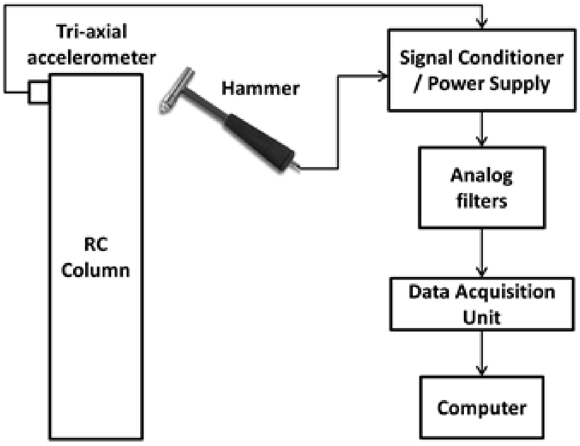

Figure 7: The vibration test set-up.

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