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Non-destructive techniques for early damage detection for highway bridges using dynamic response

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ABSTRACT:

Nondestructive techniques are based on the comparison of the static and dynamic behaviors of intact structures and their behavior in later times. The techniques are based on detection of any damage or deterioration through the structural behavior. One of the effective methods used in damage detection is based on the dynamic response of the structure to random excitation. The random decrement method is used to extract the free vibration response of structural systems subjected to Gaussian random loads with zero mean. The free vibration of the system depends on the mass and stiffness matrices of the system. When the mass and/or stiffness matrices change, the free response will also be changed. The random decrement method identifies the damage through the change of the system properties. The random decrement is usually used for single channel readings. However, in this work it is extended to use multi-channel to extract multi-signature for the structure from the dynamic response of the multi-degree-of-freedom systems. The proposed research aims to apply the random decrement technique as a nondestructive method in identifying the damage existence and location in concrete bridges. Moreover, one of the successfully used methods on data taken from finite element analysis is the modified mode shape difference method. The method can be used to extract the mode shapes of the structure without knowing the exciting force under the condition that excitation force should be stationary with zero-mean Gaussian process. The proposed work will include three models; single span, two-span simply supported bridges and a slab type bridge. Since bridges are subject to moving dynamic loads, the models will be tested by using different locations to inspect the best places to excite the structures.

1 INTRODUCTION:

Damage detection in civil structures using dynamic characteristics of the system is getting more focus in recent years. The dynamic response based methods have the advantage of detecting damages that occur inside the structures and has no signs in the exterior. Detection of damage existence in early stages allows for intervention without the loss of lives or property. The non-destructive damage techniques play an important rule for early detection of such damages. One of the simple and stable methods that can be applied to extract the dynamics parameters of bridges is the random decrement technique (RD). The random decrement was originally introduced by Cole in 1968 and was applied to detect the damping in a space shuttle wing (Cole, 1968). The method was improved later in terms of triggering conditions (Ibrahim et al. 1998). The random decrement was applied to detect damage in offshore structures (Yang et al. 1984; Elshafey et al. 2008). The method was extended to include multichannel random decrement. The mode shapes were extracted by the random decrement for the excited modes (Elshafey et al., 2009; 2010). The mode shapes when accurately extracted can be used as tool for damage detection and determining its location in the structure.

Many researchers were interested in damage detection in civil structures. The modal curvature (MC) technique for damage localization in concrete bridges was investigated and applied for real bridge (Abdel Wahab and De Roeck, 1999). The artificial neural networks were applied for damage detection in steel truss bridges (Pandey and Barai, 1995). Mazurek investigated the influence of significant damage and its location on the flexural modes of vibration in a simply supported beam (Mazurek, 1992). Adoptive local analysis technique based on local response of the structure using wavelet packet decomposition was applied to detect damage in bridges (Medda and DeBrunner, 2009). Neural networks for pattern recognition and dynamic response from finite element simulated data were used for identification of damage in suspension bridges (Yeung and Smith, 2005). Modal flexibility and modal strain energy techniques were applied on finite element generated data to assess the structural health (Shih et al., 2009). A fibre optic structural health monitoring system was developed to detect gradual and sudden damage in fractural critical bridges (Doornink et al., 2006). Several damage detection methods based on vibration monitoring were evaluated by applying them on real case bridges. Most of the methods showed that they are much affected by the noise existence (Cruz and Salgado, 2008). The change in static forces in cables was used as a base for damage detection in cable-stayed bridges (Hua et al., 2009).

Early detection of damages in bridges is crucial in saving lives, time and money. The main objective of this paper is to apply the concept of multichannel random decrement to extract the mode shapes of concrete bridges and to use the obtained modes to detect the damage existence, and location. The paper also targets to find out the best places to excite the structure to obtain clear modes. The white noise loading will be used to excite the bridges structure.

2 THE RANDOM DECREMENT TECHNIQUE (RD)

The basic concept of the random decrement technique is based on the fact that the random response of a structural system under random excitation is composed of two components: a deterministic component and a random component. The random component is assumed to have a zero average. By averaging enough samples of the random response, the random component of the response will average to zero leaving the deterministic components of the response which gives the random decrement signature. For a multi-degree of freedom structure, the dynamic response equation can be written as

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\} \tag{1}$$

Where $[M]$ is the mass matrix, $[C]$ is the damping matrix, and $[K]$ is the stiffness matrix. The response vector is denoted by $\{x\}$ and the exciting force by $\{F(t)\}$. A dot on the symbol means time derivative. The random decrement extracted from equation (1) represents the free decay of the structure. The advantage of the approach is to obtain the free decay of the structure from its stationary random response. To obtain the random decrement from the stationary random response, the response signal should be divided into N segments, each of length τ. All the segments should start with same initial condition which is called the triggering condition, $x_i(t_i)$. These segments will also have initial slope with alternating signs. The random decrement approach can be expressed mathematically as

$$x(\tau) = \frac{1}{N}\sum_{i=1}^{N} x_i(t_i + \tau) \tag{2}$$

The triggering value can be expressed as

$$x_i(t_i) = x_s \qquad \text{for} \qquad i = 1,2,3,\dots,N$$

$$\dot{x}_i(t_i) \geq 0 \qquad \text{for} \qquad i = 1,3,5,\dots,N-1$$

$\dot{x}_i(t_i) \leq 0 \qquad \text{for} \qquad i = 2,4,6,\dots,N$

The random decrement does not required knowledge of the excitation $\{F(t)\}$ and can be done without interrupting the normal operation of the structure. The excitation force should be stationary with zero-mean Gaussian process.

3 MULTI-CHANNEL RANDOM DECREMENT TECHNIQUE (MCRD)

Since we deal with multi-degree of freedom systems, only one channel will be used to apply the triggering condition as shown in Figure 1. This channel is called the leading channel. The other channels will use the times corresponding to the triggering condition and we will call these times the triggering times. The multi-channel random decrement can be expressed as

$$RD_L = \frac{1}{N}\sum_{i=1}^{N}\{X_L(t_{iSL}+\tau)|X_L = X_S\} \tag{3}$$

$$RD_{NL} = \frac{1}{N}\sum_{i=1}^{N}\{X_{NL}(t_{iNL}+\tau)|t_{iNL} = t_{iSL}\} \tag{4}$$

RD_L is the random decrement for the leading channel and $RD_{NL}$are the random decrements of the non-leading channels. X_L is the triggering condition for the leading channel, $t_{iNL}$are the times corresponding to the triggering values for the leading channel. In this paper, the constant positive value triggering condition is used. A value of the standard deviation is usually used as a triggering value for the leading channel. A FORTRAN computer code was written to extract the MCRD. The developed code allows the use of different time intervals rather than the ones used in recording the signals by applying interpolation between the recorded values. This technique has been proved to be efficient in obtaining accurate signatures.

The random responses corresponding to a specific mode are used to generate the multi-channel random decrements for that mode. The multi-channel random decrements are then used to extract that mode. A filtering process should be used to separate the contribution of each mode from the overall response of the structure. To know the range for filtering, fast Fourier transform (FFT) is applied to the time history of the response at one or more channels to know the excited modes.

4 MODE SHAPES EXTRACTION USING MCRD

The normalized random decrements obtained from the leading and non-leading channels are proved to be typical and hence they represent the free response of the structure at these points (Elshafey et al., 2010). The equations of free vibration at those points can be expressed as

$$x_i(t) = A_i e^{-2\xi\omega_i t}\cos(\omega_i t - \phi_i), \qquad i = 1,2,\dots,N \tag{5}$$

Where $x_i(t)$ are the random decrement for the i^{th} channel, N is the number of channels, A_i is the amplitude at $t=0$, ξ is the damping coefficient, ω is the natural frequency, and ϕ is the phase angle. For the same structure and same mode, the values of ξ, ω, and ϕ are the same. Therefore the values of A_i, shown in Figure 2, give the components of the mode shape vector. The mode shape λ_i corresponding to the mode number i can be expressed as

$$\lambda_i = \{A_1, A_2, \dots\dots, A_n\}^T \tag{6}$$

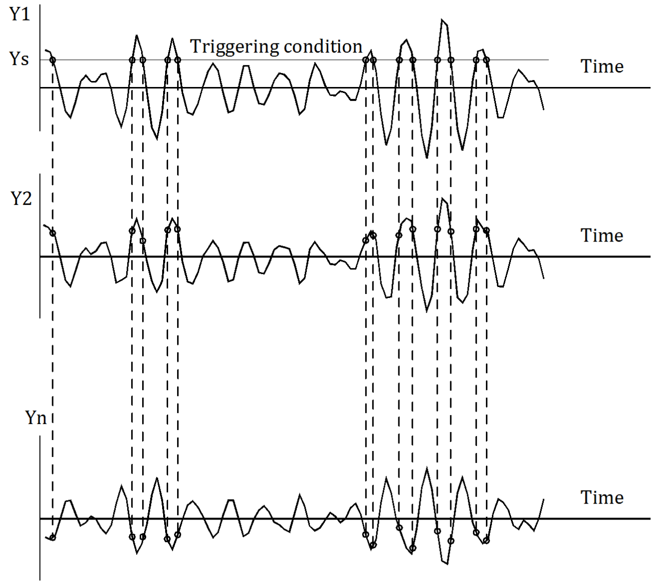

Figure 1: Multi-channel random decrement approach

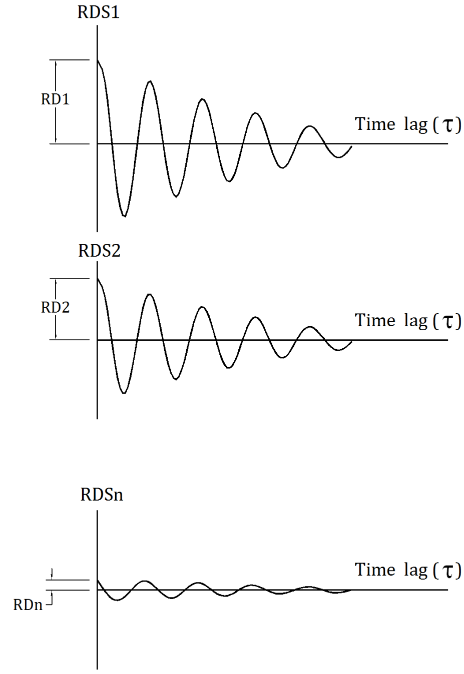

Figure 2: Multi-channel random decrements

5 MODIFIED MODE SHAPE DIFFERENCE TECHNIQUE

The mode shapes can be used to identify the damage existence and location. The algorithm of modified mode shape technique used in this work can be summarized as

- Obtain the excited mode shapes for the intact structure (each mode normalized to unity).
- Obtain the excited mode shapes for the damaged structure (each mode normalized to unity)
- Obtain the difference of the intact and damaged modes
- Normalize the difference to unity
- Add the difference as a virtual displacement to the undeformed structure
- The obtained virtual deformed structure will contain enough information to identify the damage location

6 CASE STUDIES

6.1 Single span beam

In this example, a single span concrete beam is studied. The beam dimensions and cross section are shown in Figure 3. The beam cross section is a rectangle with size of $0.20 \times 0.60m$. The material of the beam has modulus of elasticity of $2.0 \times 10^{10} N/m^2$, Poisson's ratio of 0.20, and density of $2400\, kg/m^3$. The beam is solved using the finite element approach (ANSYS software). The beam was divided into 20 elements (21 nodes). BEAM3 element is used to simulate the concrete beam. BEAM3 is a two dimensional beam element with three degree of freedom at each node; two translations and one rotation. The full transient dynamic analysis is used with a maximum time interval of 0.01seconds and a minimum time interval of 0.0005 seconds. However, the results are recorded at a constant time interval of 0.01 seconds. The nonlinear geometry was activated during the solution. The aim of this example is to test the method on simple bridges and to choose the best place to excite the bridge. The applied load has a white noise spectrum with frequencies from 0 to 50 Hz. These are enough to excite the first four modes. A time history of 100 seconds was recorded (10000 solution steps). Figure 4 shows the FFT of the displacement responses at points 11, 9, and 7 due to random load at point 5. Figures 5 and 6 show the first two modes obtained by MCRD and compared with the solution obtained by modal analysis (exact solution). To obtain these modes, the random load was applied at node 9. To see the best place to excite the structure, the load was applied at nodes 11, 9, 7, 5, and 3, respectively. The simple span bridges can be excited for the first three modes with satisfactory accuracy if the load is applied at a distance around one quarter to one third of the span measured from the the mid-point. From Figures 5 and 6, it can be concluded that the MCRD can successfully extract the mode shapes with excellent accuracy. For the first and second mode, the solutions are identical.

6.2 Double span beam

In the first case study, we showed that the MCRD can extract accurately the mode shapes which were excited by the external load. These modes can be used to identify the damage existence and location. In this example we will apply the method on a two-span simply supported beam. Damage on the element # 25 was introduced in the form of a reduction of its EI by 50% of the intact state. The beam finite element model is similar to the single span beam. The beam dimensions, material and cross section are also the same. The two spans are equal. The length of each is $10m$ and the supports are simple supports. The beam was subjected to random load as the load applied in the first case study. Figure 7 shows the change in the FFT function at point 7 with the damage existence.

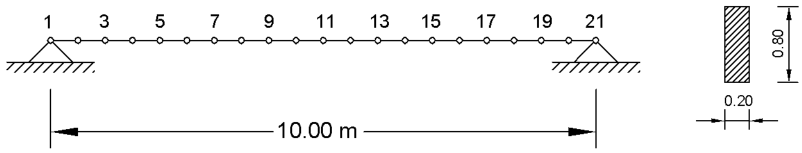

Figure 3: single span beam dimensions

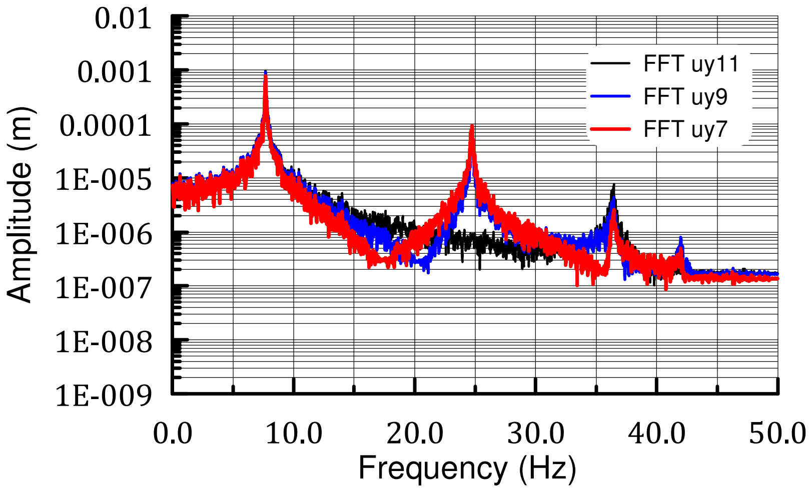

Figure 4: FFT of the response at points 11, 9, and 7 due to load application at point 5

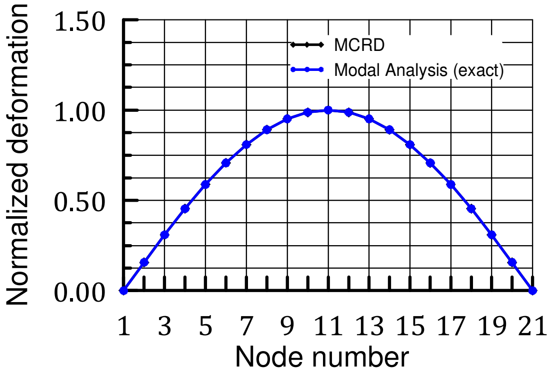

Figure 5: Mode 1 comparison (MCRD vs. Exact)

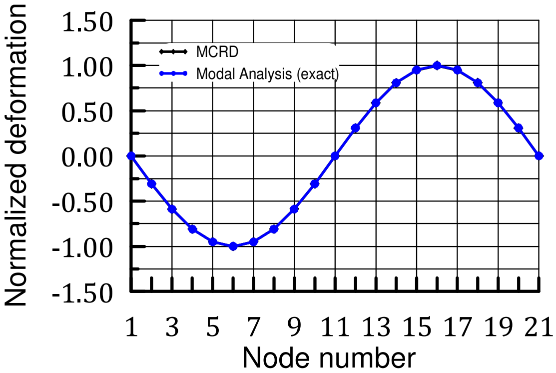

Figure 6: Mode 2 comparison (MCRD vs. Exact)

FFT can be used as a tool to indicate the damage existence without the knowledge of its location. This tool may not be very powerful as the change in the natural frequencies of the structure is not significant especially with small damages or cracks. Figure 8 shows the normalized difference between the intact and damaged mode shapes of the beam for the first mode. It can be seen from the figure that at the ends of elements 25 (nodes 25 and 26), there is a discontinuity for the difference function and the function looks to be broken at this element. The same conclusion is obtained from Figure 9 for the second mode shape.

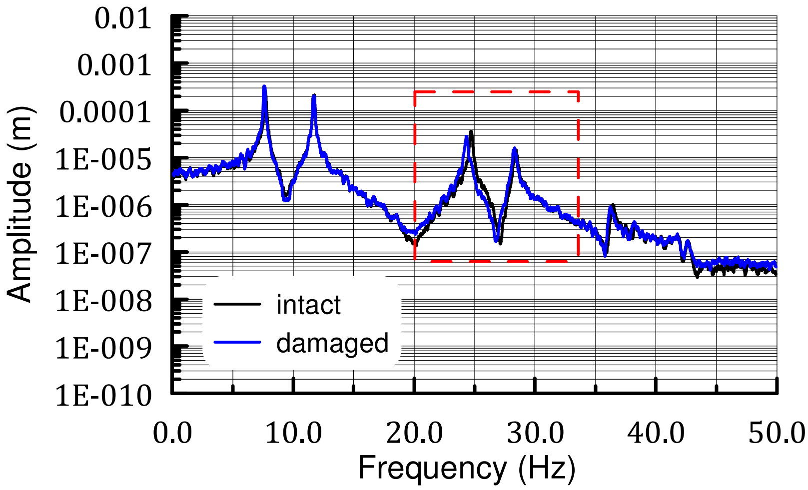

Figure 7: FFT at point 7 for intact and damaged beam

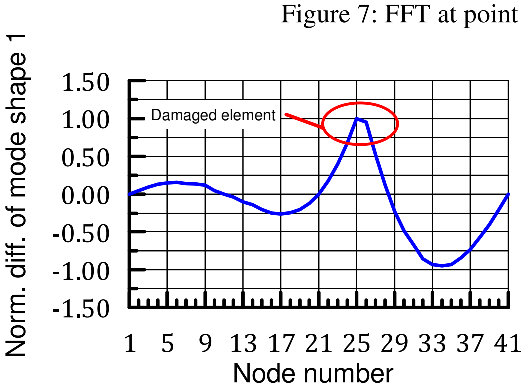

Figure 8: Normalized difference of mode shape 1 between intact and damaged beam

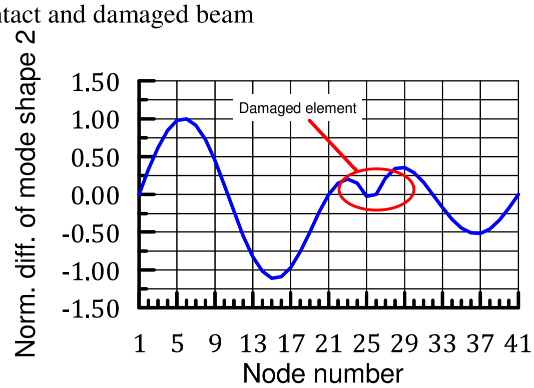

Figure 9: Normalized difference of mode shape 2 between intact and damaged beam

6.3 Slab bridge with single span

The MCRD was successful in identifying the damage in beam like structures. It is worthy to try the approach on slab like structures. This example discusses a small slab bridge made of concrete. The dimensions of the slab are $8.0 \times 3.50 \times 0.30m$. The bridge is simply supported at both ends. The structure is modelled by SHELL181 elements. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. The damage was introduced in the form of a reduction of EI by 50% for the elements 51 and 52 as shown in Figure 10. The mode shapes for the intact and damaged slab were extracted. Then the normalized difference is plotted at different nodes. Figure 11 shows an isometric view of the normalized difference of the first mode shape between the intact and the damaged structure. The damage is clearly identified in Figure 11. The isometric view of the normalized difference of mode shape 2 is shown in Figure 12. The two modes used are bending modes. The damage may not be clear on torsional modes as it is clear on bending modes.

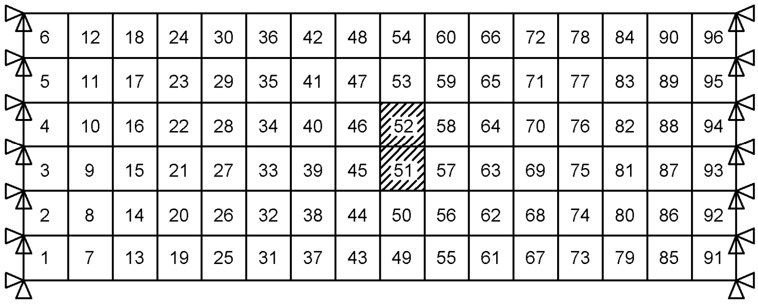

Figure 10: location of damaged elements

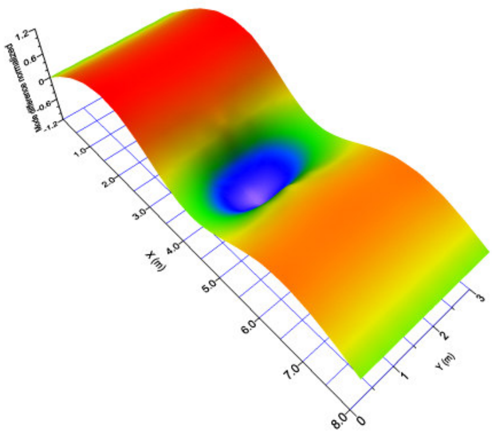

Figure 11: Isometric view of the smoothed surface of the mode 1 difference

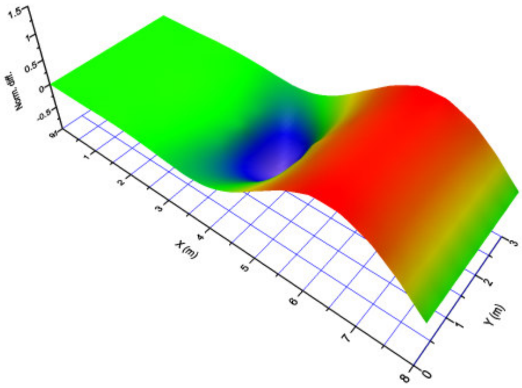

Figure 12: Isometric view of the smoothed surface of the mode 2 difference

7 DISCUSSIONS AND CONCLUSIONS

This work presented the applications of the multi-channel random decrement method (MCRD) in extracting the mode shapes for a simple span bridge including both beam and slab like structures. The method was successful to extract the excited modes accurately from the random vibration of the structure. The first two modes extracted by the MCRD technique were identical to the ones obtained from modal analysis. Some small error was noticed in the third mode but still the results are very good.

The method can be applied without knowing the exciting force under the condition that the force has a white noise spectrum with zero mean. However, it can be applied for narrow banded spectrums to extract the mode shapes excited by the load. The approach was illustrated in details and applied on several case studies. Filtering process is needed to separate the responses corresponding to different modes. The modified normalized mode shape difference was introduced and applied to identify the damage in bridge structures. The method is so far successful on numerically generated data.

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