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Monitoring of Damage in a R. C. Beam based on Changes in Phase Angle

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ABSTRACT:The technique measures the phase angle difference between two measuring channels with healthy structure as reference data and monitors the vibration measurement of the structure to detect and localize damage. One assumption made is that the amplitude, location and waveform of the excitation forces for undamaged and damaged structure shall be same. The proposed method uses only the measured data without need for any modal identification. The method thus developed is applied to a reinforced concrete beam model to detect the damages induced in the beam. Some damage scenarios were introduced to the beam. The damage was thus detected and located accurately using the proposed change in phase angle method. The method could also detect damage at multiple locations accurately based on the vibration response.

KEYWORDS: Prognosis, Damage detection, Localization, Modal parameters, Health monitoring, Phase angle, Cross Spectral Density

I. INTRODUCTION

Non destructive evaluation (NDE) methods do not provide quantitative values to asses the remaining strength of structure accurately. A number of bridges across the world are overused and overloaded, and requires urgent structural action. This idea has mooted considerable research efforts to develop practical structural health monitoring systems [1, 2] that can accurately assess the damage. In the recent past, good number of works have been undertaken to address non-destructive damage evaluation via changes in the dynamic modal responses of a structure [3, 4].

Modal parameters such as mode shapes, resonant frequencies and damping are functions of physical properties of the structure viz., mass, stiffness and boundary conditions. Damage alters the physical properties of structure, which in turn changes the modal parameters. Several non-destructive damage detection techniques have been proposed based on changes in modal parameters. The basic premise of such a damage identification technique will be that for each modal response the amplitude and phase angle can be estimated. Any change in the modal response due to occurrence of damage will in turn change both the amplitude and the phase angle. In order to overcome the problem of limited number of identified modal parameters, the phase information estimated from the readings of various accelerometers at all frequencies in the measurement range and not only the modal frequencies will have to be compared before and after damage using the method suggested. To identify the damage more accurately, all the measuring channels will be used as reference for other channels as well, which automatically creates large set of data. This data is then analyzed using statistical procedures to determine the damage location with better confidence. The same is highlighted in the following sections.

Let G_{xy} (f) denote the Cross Spectral Density (CSD), relating two time histories, x(t) and y(t). The phase angle between x and y can be computed from the real and imaginary values of G_{xy} as:

$$P_{xy}(f) = \tan^{-1}\left[imag(G_{xy}(f)) / real(G_{xy}(f))\right]. \quad (1)$$

The absolute difference in absolute phase angle before and after damage can then be defined as

$$\Delta_{xy}(f) = \left\| P_{xy}(f) \right| - \left| P_{xy}^{*}(f) \right\| \quad (2)$$

where P_{xy} (f) and $P_{xy}{}^{*}$ (f) represent the phase angle of the undamaged and damaged structures respectively. When the change in phase angle is measured at different frequencies on the measurement range from f_1 to f_m , a matrix [Π_r] can be formulated as follows

$$\Pi_r = \begin{bmatrix} \Delta_{1r}(f_1) & \Delta_{1r}(f_2) & .... & \Delta_{1r}(f_m) \\ \Delta_{2r}(f_1) & \Delta_{2r}(f_2) & .... & \Delta_{2r}(f_m) \\ . & . & .... & . \\ . & . & .... & . \\ . & . & .... & . \\ \Delta_{nr}(f_1) & \Delta_{nr}(f_2) & .... & \Delta_{nr}(f_m) \end{bmatrix}_r \qquad (3)$$

where, *n* represents the number of measuring points and *r* represents the number of reference channel. In matrix [Π_r], every column represents the changes in phase angle at different measuring channels but at the same frequency value. Each measuring channel will be used as a reference for the other channels ($r = 1 : n$). Therefore, the matrix [Π_r] will be formulated *n* different times (3D matrix). The summation of phase angle changes over different frequencies using different references can be used as the indicator of damage occurrence. In other words, the first damage indicator is calculated from the sum of rows of each matrix, [Π_r] and then summing up these changes over different references

$$Total\_Change = \sum_r \begin{Bmatrix} \sum_f \Delta_{1r}(f) \\ \sum_f \Delta_{2r}(f) \\ . \\ . \\ . \\ \sum_f \Delta_{nr}(f) \end{Bmatrix}_r \qquad (4)$$

where, $f = f_1 : f_m$ and $r = 1 : n$.

This indicator is used to detect the damage.

II. SIGNIFICANCE OF THE SYSTEM

In the present work, the algorithm is applied to the experimental data extracted from a reinforced concrete beam model after inducing some defects to the beam. The introduction in the form of cutting the beam at salient portions of the beam is how the damage is introduced to the beam. The four damage stages are viz., cutting up to the cover thickness of the beam, cutting up to the neutral axis of the beam without cutting the reinforcement and finally cutting the tension reinforcement in the R.C. beam at these salient points. Using tunable piezoelectric actuators, the modal measurements could be made that could acquire the dynamic response of the damage induced more completely and accurately.

III. LITERATURE SURVEY

Modal vibration data such as natural frequencies and mode shapes can be used to characterize the state of structure [5,6]. This capability is attributed to the fact that damage in the form of changes in structural physical properties (i.e., stiffness, mass, and boundary conditions) alters vibration properties of structure such as frequencies, mode shapes, and damping values [7]. Also, the changes in vibration properties can serve as indicators of damage detection [8,9].

The acoustic or ultrasonic methods of damage-detection such as magnetic field methods, radiography, eddy-current and thermal field methods are either visual or localized experimental methods [10,11] and involve long and expensive inspection time. These drawbacks of inspection techniques have led researchers to investigate new methods to continuously monitor and assess the structures. These methods are based on vibration responses that allow one to obtain meaningful time and/or frequency domain data and calculate changes in structural and modal properties. These properties are used to develop reliable techniques for detecting, localizing and quantify damage [12]. Many damage detection schemes rely on analyzing response measurements from sensors placed on the structure [13,14,15,16,17]. Research efforts have been made to detect structural damage directly from dynamic response measurements in time domain, e.g., the random decrement technique [18,19], or from frequency response functions (FRF) [20,12,22] .

IV. METHODOLOGY

In the present paper, an algorithm is proposed based on changes in phase angle. The technique is based on the assumption that the excitation forces used for undamaged and damaged structure shall have the same amplitude, location and waveform in order to ensure that the changes in phase angle data are mainly due to damage and not due to the changes in the excitation force characteristics. The excitation force does not need to be measured. The algorithm detects damage using only the measured data without need for any modal identification. The methodology thus developed can be used in detecting damages in large civil engineering structures, such as concrete bridges. A number of sensors can be mounted on the girders of the bridge to measure the acceleration response and a number of actuators can be used as a local excitation source for the girder. The same excitation force (equal magnitude and the same waveform) is employed for exciting the undamaged and damaged structure, as required to implement damage identification technique. Undesired vibrations induced from wind, traffic or any other source can be avoided since the vibration data induced from actuators can be generated at any desired time. Moreover, traffic on the bridge need not be interrupted. The experimental models and type of damage presented simulates the applicability of the method to concrete structures.

In this research, the concepts explained earlier are used to investigate a reinforced concrete beam after inducing damage at known locations. The model is a reinforced concrete beam. The dimensions and layout of the model are shown in Fig. 1. A piezoelectric actuator is used for excitation of the beam. The piezoelectric actuator used in the present work produces vibration with different frequencies ranging from 0 to 800 Hz and is effective in exciting different mode shapes. Natural frequencies are measured in the range of the excitation frequency from 0 to 800 Hz (sweep) and also independently at 100 Hz intervals up to 800 Hz(sinusoidal). The amplitude of the actuator force is 0.3 kN. The actuator is located at the center of the top portion of the beam as shown in **Fig. 1**. The location of the actuator is not altered during different damage states of the structure. The excitation forces used for undamaged and damaged structure are uniform. The actuator is attached to the structure with a spring and is not glued to the surface of the structure. So, the actuator always provides compressive type of force and not the tensile forces. The excitation force need not be measured. A total of five accelerometers were attached on the beam to measure the acceleration response in vertical direction on the beam as shown in **Fig. 1**. The details of the characteristics of equipment used are shown in **Table 1**.

Table 1 Equipment characteristics

Piezoelectric actuator	
Dimensions (W×T×H)	10×10×20 (mm)
Min. and Max freq.	0～982 Hz
Displacement (100V)	12.3 μm
Piezoelectric accelerometer	
Dimensions (Base×H)	17 Hex × 32 (mm)
Frequency Bandwidth	5～4000 Hz
Sensitivity	10 mV/(m/s^2)

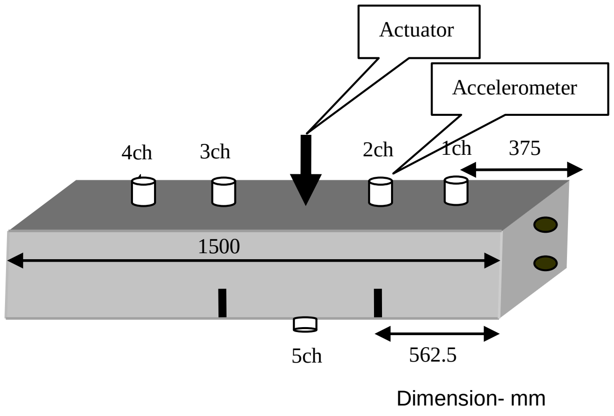


Fig. 1 Dimensions of the reinforced concrete beam tested

Several cases are examined including three damage cases and one no damage condition. The damage to the beam is introduced as follows:

Case 1: No damage case-no cut on the beam
Case 2: Cutting of the beam of 5mm width and 40mm deep till the cover portion.
Case 2: Cutting of the beam of 5mm width and up to neutral axis without cutting the reinforcement in the tension portion.
Case 3: Cutting of the reinforcement in the tension portion also.

Damage identification method applied to different damage cases

At first the Cross Spectral Density (CSD) was calculated from the node point accelerations obtained between each measuring channel and the reference channel using MATLAB [23,24] and the Signal Processing Tool box.

Then the phase angle is calculated from the real and imaginary values of CSD data. Every measuring channel will be used once as a reference also for other channels and so on. The phase angle is then measured in the frequency range of 0–800 Hz. This range is determined based only on the sampling rate of collecting the data rather than the frequency content of the excitation force. It is desirable to use phase angle data in the total measurement range ie 0-800Hz to avoid the problem of determining the best frequency range in which phase angle needs to be measured. In other words, the phase angle data can be used in the total measured frequency range regardless of frequency content of excitation force without the need to identify the best frequency range in which the phase angle needs to be used. The total change in phase angle at each channel, measured in a certain frequency range, can be determined using equation (4). The total change in phase angle for two sets of data obtained from the undamaged structure is shown in **Fig 2**.

When the total change in phase angle was calculated for another two sets of data obtained from the undamaged structure, similar results were obtained. It is assumed that damage will produce greater values of the total change in phase angle than the estimated threshold values. Therefore, the total change in phase angle will be used for detecting the occurrence of damage in the structure.

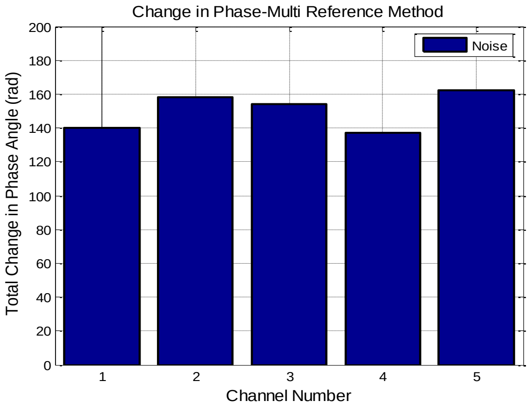


Fig 2 Total change in phase angle due to noise

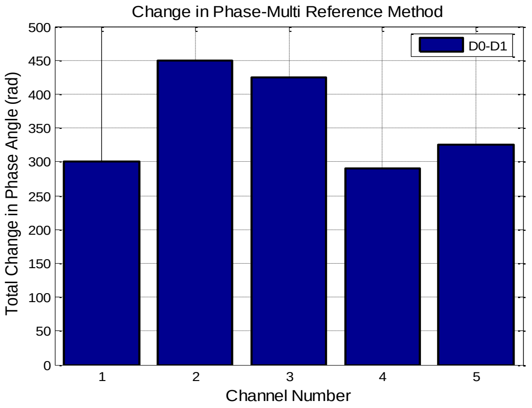


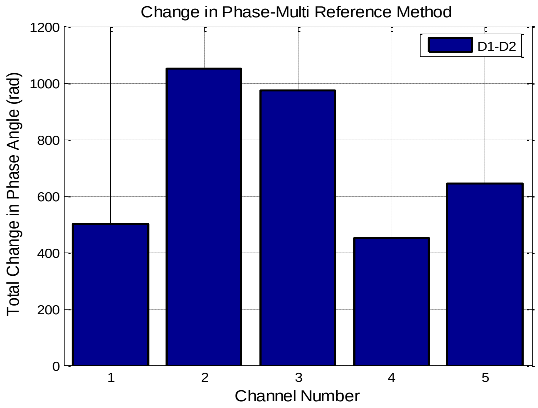
Fig. 3Total change in Phase Angle for damage Case 1

(A) Case 1 damage- Crack 5mm wide and 40mm deep

In the first damage case(D1) a crack of 5mm wide and 40mm deep is made at channel locations 2 and 3.The accuracy of the damage identification methods based on FRF or cross spectral density (CSD) is dependent on the frequency range in which FRF or CSD is measured. The entire frequency range from 0−800 Hz is used in the proposed algorithm. In **Fig. 3**, the total change in phase angle (Equation 4) increased at all channels after introducing cuts at channels 2 and 3. The total change in phase angle due to this is much larger than that due to noise and measurement errors (Fig.7). The maximum total change of phase angle is observed at channels 2 and 3.

(B) Case2 damage- Crack 5mm wide and 100mm deep

In the second damage case(D2) the damage level is increased by increasing the earlier crack of 40mm deep to 100mm ie: up to the Neutral Axis. The total change in phase angle(Eq.4) increased with the crack depth as shown in **Fig 4**.



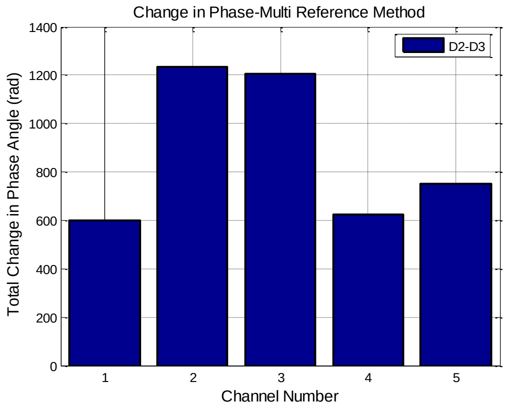


Fig. 4 Total change in Phase Angle for damage Case 2 **Fig. 5 Total change in Phase Angle for damage Case 3**

(C) Case3 damage- Cutting of bar in tension portion

In the third damage case (D3), the damage level increased by cutting the reinforcement at the locations of channels 2 and 3. These values are plotted in **Fig 5**.

A summary of the total changes in phase angle(Eq. 4) for different cases is plotted in **Fig.6**. It can be observed that the total change in phase angle due to noise is less than 200 radians at all channels and there was a close difference. After making the first cut with 4mm wide and 40mm deep (Damage D0), the total change in phase angle has increased at all channel locations. It is already known that damage even at one channel location will change the over all stiffness of the structure. However, the change in phase angle is more at channels 2, 3 and 5.

After increasing the cut up to the Neutral Axis ie; 100mm without cutting the reinforcing bar in the tension portion of the RC beam, the total increase in phase angle contributed to slight values at the undamaged locations 1 and 4, while it is more at damage locations 2 and 3. Channel 5 is in between locations 2 and 3, and hence, there is a reasonably more change at 5 compared to channel locations 1 and 4. After increasing the damage further by cutting the reinforcing bar in the tension portion, the total change in phase angle increased further and like earlier case the change was more at the locations 2, 3 and 5.

The relative change in phase angle after the reinforcing bar cut was less compared to earlier damages. It can hence be concluded that the total change in phase angle monitored the increase in damage successfully in the reinforced concrete beam.

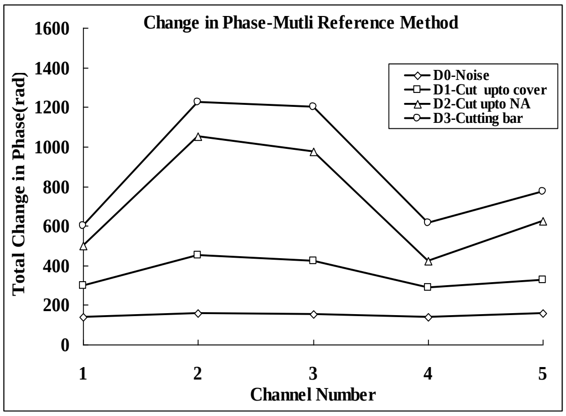


Fig. 6 Total change in phase for different damage cases

VI. CONCLUSION AND FUTURE WORK

The experimental results obtained from the reinforced concrete beam demonstrated the superiority of changes in phase angle magnitude as a diagnostic parameter for detecting the damage in a structure. The proposed approach is a global

NDE method which uses vibration measurements and is used to identify structural damages that produce measurable alterations in the structural dynamic characteristics. The excitation forces used for the undamaged and damaged cases for the structure shall have the same amplitude, location and waveform in order to ensure that changes in phase angle data are mainly due to damage and not due to change in the excitation force characteristics. The proposed method uses the measured phase angle in a certain frequency range without the need for any modal characteristic data. The phase angle can be used in the total measured frequency range without the need to determine the best frequency range that gives the most accurate results.

The proposed method exhibited better results in identifying the changes in phase angle associated with damage from changes attributed to noise or measurement errors. The total change in phase angle method could monitor the change (increase) in damage successfully in reinforced concrete structures. Other methods of damage detection and localization like PSD, TFE etc may also be explored.

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