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Damage Identification of RC Structures using Wavelet Transformation

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Abstract

Vibration based techniques are gaining popularity for damage detection, precise localization and damage quantification. These techniques involve recording of the vibration signatures and their analysis for temporal and spectral characteristics to arrive at conclusive statement. Among different damage identification techniques, most of the algorithms are model based approaches and lacks standardization and accuracy. In this paper, feasibility of using output-only model-free wavelet based techniques for damage identification of 6-storied scaled reinforced concrete (RC) building is studied. The vibration signals at different floor levels of the RC building were acquired using wireless accelerometers. The vibration measurements were carried out for different cases i.e. bare frame and varying mass at different floors. The signal discontinuity of the acceleration response of RC building was extracted using complex continuous Gaussian wavelet transformation and analysed. The results show that wavelet coefficients are directly influenced by the change in physical properties of structure and are able to detect damage to a reasonable extent.

Keywords: Damage Identification; Reinforced Concrete building; Wavelet Analysis; Structural Health Monitoring.

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1. Introduction

Damages often occur in building structures during its service-life and sometimes, if undetected, lead to structural failure endangering life safety of occupants. In recent years, special attention is given to study the occurrence of damage in building structures in early stage to avoid sudden failure.

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Structural Health Monitoring (SHM) based on the vibration measurements are utilized as one of the tool to determine the presence of damage, its location, extent and prognosis of remaining service life. There are many damage detection systems that are used around the world, but there is no standardized technique that can be trusted by engineers [1]. The fundamental basis for these vibration-based damage identification techniques is that the damage induces change in the physical properties (mass and stiffness), leading to change in modal properties (natural frequencies, modal damping, and mode shapes) of system. For example, crack development leads to reduction in stiffness of the buildings. Hence, it is intuitive that damage can be detected by evaluating the changes in vibration response of the buildings.

Doebling et al. [2], Sohn et al. [3], Carden & Fanning [4] and Fan & Qiao [5] conducted detailed survey for structural health monitoring and damage detection studies on different structural systems. Development of damage detection algorithms in last three decades from basic frequency change based methods to advanced signal processing and artificial neural network based approaches have been discussed by the reviewer’s in detail. Among the various researched techniques time–frequency and time-scale analysis techniques, particularly the wavelet analysis tool have been proven to be among the successful methods for assessment of structural health and damage detection. Early studies utilizing wavelet analysis were conducted for local damage detection in machineries [6, 7]). Similar studies have been carried out to identify damage in bridges by establishing variation in wavelet coefficients of time-history responses [8]. Hou et al. [9] studied accumulated damage due to the San Fernando earthquake excitations and detected the change in structural stiffness from spikes in the wavelet coefficients using multi-resolution analysis (MRA). Damage assessment of bridges based on energy calculation was carried out by Sun and Chang [10] using a wavelet packet transform (WPT) and neural networks. Modal curvature approaches are able to identify location of damages in a structure. But this approach is not robust for damage identification. Amaravadi et al. [11] proposed use of wavelet transform (WT) over the curvature mode shape for increased accuracy in damage identification. Gurley et al. [12] identified first and higher order correlation by using a CWT to construct filtered wavelet coherence and bi-coherence maps to observe offshore structures. Melhem and Kim [13] carried out work to identify damage on full-scale concrete structures using a CWT and wavelet ridges. Kim and Melhem [14] reviewed the literature on damage detection in beams, mechanical gears and rollers using discrete wavelet transform (DWT) and CWT. Ovanesova and Suarez [15] analyzed static deflected shape of beams and frame structures using WT for damage detection. CWT has been used to identify stiffness degradation in structures [16, 17].

Wavelet-based damage identification approaches are primarily associated with detecting singularities in the response signal either in space or in time or any of their derivatives [18]. Damage identification in beams using spatial wavelet analysis is also a problem of singularity detection in the vibration response. Radzienski and Krawczuk [19] induced vibrations to an aluminum plate, fixed with symmetrically riveted stiffeners in rows, using an electromechanical shaker and recorded the response of system with non-contact scanning laser Doppler vibrometer. Authors compared various damage identification techniques and concluded that WT is most effective, noise independent and versatile damage identification technique. Vibration responses from RC structures were studied using wavelet analysis for damage feature extraction [20, 21, 22]. Chen et al. [23] used DWT using Daubechies family wavelets to identify the effect of induced damage in dynamic response from a 5-storey building and observed that the first level detail coefficients of WT at damage instant is proportional to the magnitude of the stiffness reduction.

Nomenclature

R	real number
$x(t)$	signal
t	time
f	frequency
s	scaling parameter (denotes window width)
τ	shifting parameter (denotes location of moving wavelet window)

Gentile and Messina [24] studied the selection criteria for a wavelet basis function in the presence of noise and demonstrated the performance of Symlet and Gaussian wavelets. Complex Gaussian, complex wavelet and complex frequency B-spline wavelet functions were applied on time history responses from four stories of ASCE benchmark steel frame structures to study effect of wavelet function choice on calculating modal parameters.

This paper discusses the applicability of WT on experimentally obtained vibration responses from a framed scale-down 6-storey RC building, constructed for health monitoring studies. Application of WT for damage identification from experimentally recorded vibration response is preceded by brief description of wavelet transform.

2. Wavelet Transform

Signal processing transforms a time domain signal to into another domain signal usually frequency domain as information embedded in time domain cannot be readily observed. Fourier Transformation is among the first introduced signal processing tools used to get frequency composition of stationary time series signal. Fourier Transformation, *X(f)*, of a signal *x(t)* is defined with Eq. (1).

$$X(f) = \langle x, e^{i2\pi ft} \rangle = \int_{-\infty}^{\infty} x(t) e^{-i2\pi ft} dt \tag{1}$$

FT is often used to get natural frequency of civil structures but this classical theory of FT has few drawbacks e.g. FT does not reveal any time dependency of frequency in the signal. Also, suitability of FT for non-stationary signals is quite inappropriate. In order to overcome these drawbacks, Gabor introduced short time Fourier transform of signal *x(t)* using Eq. (2).

$$STFT(\tau, f) = \left\langle x, g_{\tau,f} \right\rangle = \int x(t) g^{*}_{\tau,f}(t)\, \mathrm{dt} = \int x(t) g(t-\tau) e^{-i2\pi ft} dt \tag{2}$$

where τ denotes the location of window and g is windowing function.

Basically, STFT is a windowed Fourier transform. A fixed size window is introduced in FT and signal is transformed to joint time-frequency domain. But the particular fixed window may not be appropriate for all frequencies contained in the signal. Also, as per Heisenberg uncertainty principle, defined by Eq. (3), one cannot obtain high resolution in both time and frequency simultaneously.

$$\Delta s.\Delta f \geq \frac{1}{4\pi} \tag{3}$$

where Δf =frequency resolution and Δs =time resolution.

In contrast to short-time Fourier transform, Wavelet transformation (WT) is a powerful tool incorporating variable window size. Daubechies [25] and Mallat [26] defined the usability of wavelets in digital signal processing and opened the new area of wavelet application. Wavelet is a small wave, in comparison to infinite waveform in Fourier Transform, centered around a point in time with fast decay to zero away from center. With WT balanced resolution can be obtained in both time and frequency of a signal. Using notation of inner product, continuous wavelet transform (CWT) of a signal *x(t)* is expressed satisfactorily by Eq. (4).

$$CWT(s,\tau) = \left\langle x, \psi_{s,\tau} \right\rangle = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \psi^{*} \left(\frac{t-\tau}{s} \right) dt \tag{4}$$

$$s, \tau \in R, s \neq 0$$

where s = scaling parameter (denotes window width)

τ = shifting parameter (denotes location of moving wavelet window)

$\psi(\frac{t-\tau}{s})$ = base or mother wavelet

$\psi^*(\frac{t-\tau}{s})$ = complex conjugate of mother wavelet $\psi(t)$

Complex wavelets are able to give modulus coefficients as well as phase details. Complex Gaussian wavelets offer increased match to hidden sinusoidal looking events. Also, at each level of differentiation a combination of symmetric and anti-symmetric wavelets is observed for real and imaginary parts, which allows for better applicability for vibration analysis. Complex Gaussian wavelet is defined by Eq. (5).

$$Cgau(t) = cos(t)*exp(-t^2) + (i*Sin(t))*exp(-t^2) \qquad (5)$$

3. Damage Identification in Reinforced Concrete Building

3.1 Experimental Setup

Six-storey 1/3 scaled reinforced concrete (RC) building was constructed in CSIR-CBRI, Roorkee campus for carrying out the health monitoring studies. The structural configuration of RC building is detailed in Table 1.

Table 1: Structural configuration of RC test structure

Parameter	Structural detail
Number of storeys	06
Grade of concrete	20 MPa
Grade of steel	415 MPa
Plan dimension	1.5 m * 2.0 m
Storey height	1.1 m
Column section	150 mm * 150 mm
Beam section	100 mm * 155 mm
Slab thickness	65 mm

Tri-axial wireless accelerometers were fixed on 2nd, 3rd, 4th and 5th floor levels of RC building to acquire acceleration-time histories in both ambient and forced excitation condition (Fig. 1). Wireless accelerometers were programmed for synchronized sampling and data logging with the Node commander software. To capture the vibration data with lesser noise, these sensors were fixed with screws on the aluminum plates fixed at outer surface of beam at center. For forced conditions, long stroke shaker with attached mass assembly was placed at 5th floor (Fig. 1) to excite the RC building at known frequencies. The building was subjected to sine-sweep excitations with frequency increasing linearly from 3.6 to 4.6 and 4 to 5 Hz in 30 seconds separately. For the presented cases, the sine-sweep input excitation ranged from 3.6 to 4.6 Hz and the acceleration time history was recorded for intervals of 30 seconds each, from 2nd to 5th floors simultaneously, at sampling rate of 256 samples per second. Load on known floor was varied while recording the vibrations and data was processed with wavelet transformation to identify the location of change. Few selected cases out of numerous experiments carried out, are given in Table 2.

Table 2. Details of experiments with addition of mass on 6-storey RC building

Load case	Floor level	Additional load (kg)
1	3rd	9.0
2	3rd	13.0
3	3rd	19.5
4	3rd	25.0
5	3rd	35.0
6	3rd	52.0
7	3rd	65.0
8	3rd	78.0
9	3rd	91.0

3.2 Results and Discussion

The first modal frequency of RC building along shorter direction was observed to be 4.61 Hz in ambient state, which reduced to 4.16 Hz when RC building was subjected to 3.6-4.6 Hz sine-sweep excitation, using long stoke shaker (weighing 51 kg) placed at 5th floor. It was also observed that the modal frequency of building decreased with increase in mass at different floor levels. The addition of external load / mass at the floor level induces change in physical properties of building and adds singularity to the recorded vibration responses. This recorded response was analyzed using complex Gaussian ‘cgau5’ wavelet, using MATLAB wavelet toolbox, to find out the singularity in the signal in terms of wavelet coefficient modulus. Obtained wavelet coefficient modulus were observed to be maximum corresponding to the floor (third) at which sudden variation of load was done, as compared to other floor levels (Fig. 2).

It was observed that additional load could not be detected in case 1 where only 9 kg mass was added to 3rd floor. This may be attributed to the fact that added mass of 9 kg was very less in comparison the floor mass of 960 kg (0.93%). In all other cases location of additional mass could be identified accurately when building was subjected to forced excitation as the discussed cases. Also, the developed methodology for detection of the location of change in structural properties is independent of any base line data i.e. any pre-acquired vibration response for comparative purpose is not required. Hence, this method is output-only modal-free damage identification algorithm and hence can be applied where other comparative basis approaches are not suitable for damage detection.

Fig. 1. Scale down six storey RC building constructed and monitored for health monitoring studies

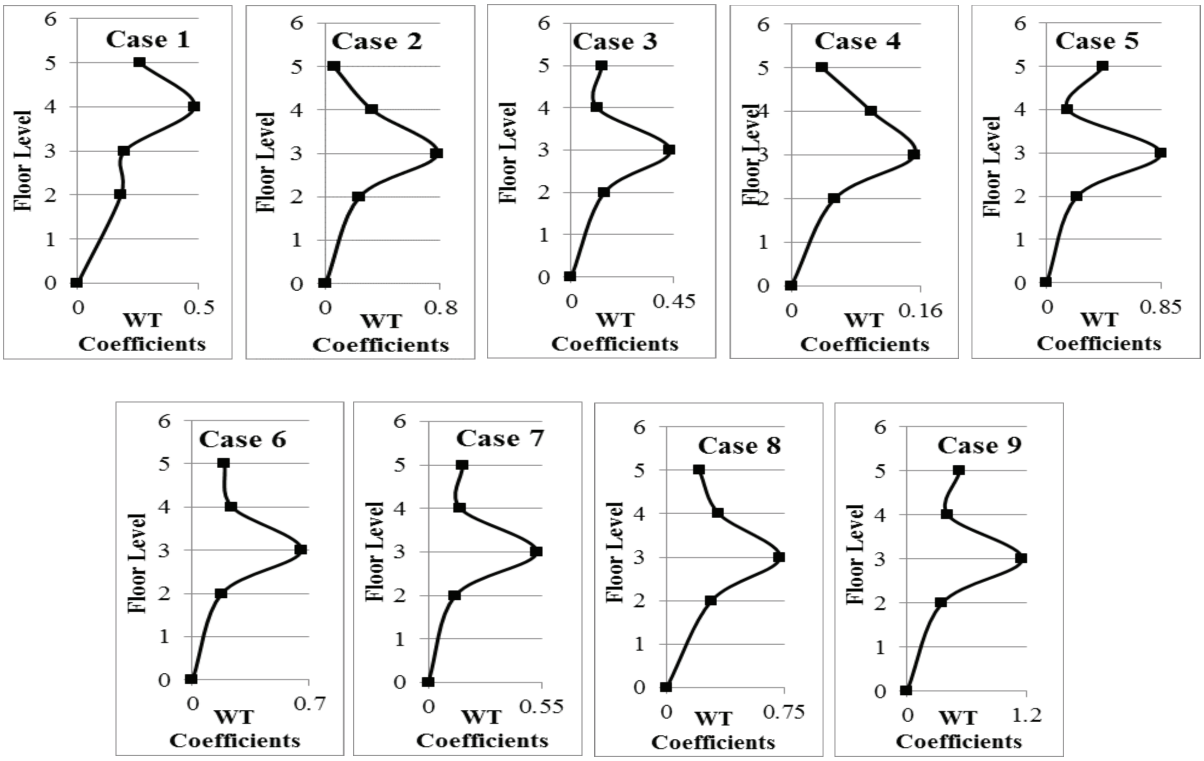

Fig.2. Identification of location of load variation on 6-storey RC building using wavelet transformation

4. Conclusion

This paper proposes a new wavelet based method applying complex continuous Gaussian wavelet transformation for identification of induced damage in a structure. The proposed methodology is easy and simple to use. It is based on application of wavelet transform on the vibration response of real time monitored structures and finding the location of maximum wavelet coefficient. Changes in behavior of wavelet transform coefficients at different scales (corresponding to different frequency) were observed and used to locate the level at which mass was added. Hitherto, the wavelet transform based approach is capable of identifying the location of change of building's physical properties with increased accuracy. More laboratory scale controlled experiments may be performed to quantify damage, adding further knowledge to present work. Also, the proposed methodology needs to be validated for detection of low level stiffness reduction due to small cracks in the building structures.

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