Structural condition assessment from recorded earthquake response data

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Abstract

Monitoring of changes in vibration response has been widely used for assessment of structural integrity, performance and safety. In particular, on-line health monitoring and diagnostic assessment of critical infrastructure becomes vital after the occurrence of extreme events such as earthquakes and blast loads. However, it is found difficult, if not impossible, to characterize structural condition and detect time-varying, non-stationary spectral characteristics using the traditional frequency spectrum analysis method. In this paper, a wavelet signal analysis technique is implemented for post-earthquake damage assessment directly from recorded response data. The results obtained from numerical simulations and real response data from moderate to severe earthquakes indicate that wavelet analysis is a powerful tool that can be used to identify hidden transient characteristics and high energy bursts that may occur due to progressive structural stiffness degradation and/or pounding between structural components. The appearance of multiple closely spaced transient peaks in the details of the wavelet decomposition coefficients is used for the assessment of the occurrence of progressive damage in the structural system. Finally, the structural response behavior during earthquake excitation is characterized from a critical investigation of the details of the local high frequency signal energy variations in the time-frequency domain.

Introduction

The occurrence of high dynamic loading events such as earthquakes and blast loading may cause damage to civil engineering structures, including microcracking, flexural cracking, shear and bond slippage, crushing of concrete and yielding of reinforcement. Visual inspection of these types of damage may not be reliable to establish condition states of structural integrity and safety. In the last few decades, vibration-based non-destructive damage identification and health monitoring techniques have been widely used in the areas of aerospace, automotive, civil and mechanical engineering (Doebling et al, 1996). The majority of these techniques are based on common simplifying assumptions regarding structural linearity and response stationarity and require two sets of measurements, one from each of the undamaged and possible damaged states in order to achieve the desired results. However, for cases involving time-varying processes and nonlinear damage mechanisms, such as breathing cracks, sudden loss of stiffness and damage in composites, traditional fast Fourier transform (FFT) based damage identification methods are no longer effective.

In this application oriented paper, the use of a wavelet analysis approach is proposed for post-earthquake damage condition assessment and response characterization directly from acceleration response records. Wavelet analysis is a novel signal analysis tool which has been widely used in numerous fields of study (earth science systems, engineering geophysics, medical physics, astronomy, remote sensing) for signal processing, pattern recognition and image compression. In the past, wavelet analysis has been extensively applied for characterization of a non-stationary signal, denoising, nonlinear system identification and detection of transients (Brenner, 2003; Basu and Gupta, 1997; Gurely and Kareem, 1999); machine condition monitoring and fault diagnostics (Peng and Chu, 2004); structural damage detection and long-term health monitoring (Hou et al, 2000; Kim and Melhem, 2003; Moyo and Brownjohn, 2005). These studies demonstrate the strong promise that wavelets offer to a wide range of studies. However, their application to practical problems such as post-earthquake condition assessment is not yet fully exploited. In this regard, this paper demonstrates the application of wavelet analysis on simulated data and earthquake records, in particular.

The wavelet transforms

Signal analysis using wavelet transforms involves decomposition of a one-dimensional time series signal into two-dimensional time-frequency space by using a series of basis functions of the translated (shifted) and dilated (stretched) analyzing (or mother) wavelets. Detailed information regarding the theoretical treatment of wavelets is given in Daubechies (1992). In general, wavelet transforms can be applied in two ways: the continuous wavelet transform (CWT) or the discrete wavelet transform (DWT). The CWT is defined as the sum over all time of the signal multiplied by a scaled, shifted version of the wavelet function, as follows:

$$Q(\alpha,\beta) = \frac{1}{\sqrt{\alpha}}\int_{-\infty}^{\infty} y(t)\psi^{*}(\frac{t-\beta}{\alpha})dt \qquad (1)$$

where wavelet coefficients, Q, represent a regression of the signal $y(t)$ on the wavelet. α and β are the scale index (dilation factor) and the translation factor (or time shifting), respectively. ψ^{*} is the complex conjugate of the mother wavelet. Similarly, DWT can be defined mathematically using the discrete wavelet function and the associated scaling function.

Finally, wavelet transforms-based features that have significant areas of application, such as wavelet power spectrum (WPS), wavelet cross power spectrum (WCS) and wavelet coherence (WCO), can be defined as follows (Torrence and Compo, 1998):

$$WPS(\alpha) = \left|Q(\alpha,\beta)\right|^{2} \qquad WCS(\alpha) = \left|Q(\alpha,\beta)^{X} Q^{Y*}(\alpha,\beta)\right|$$

$$WCO(\alpha) = \frac{\left(s\alpha^{-1}WCS(\alpha)\right)^{2}}{s\left(\alpha^{-1}WPS^{X}(\alpha)\right).s\left(\alpha^{-1}WPS^{Y}(\alpha)\right)} \qquad (2)$$

where WPS finds regions of high power in the time-frequency domain; WCS reveals areas of high common power and phase relationship of two processes; WCO provides normalized correlation and phase locked behavior of two processes; and s is a smoothing operator.

Simulation studies

Identification of breathing crack condition in a SDOF system

In this section, the merit of using wavelet transforms over FFT based methods is demonstrated with respect to localization of breathing cracks and their associated

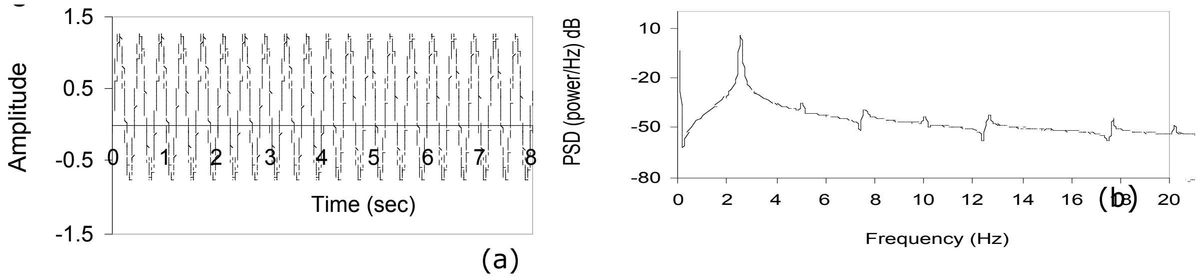

Figure 1 Free vibration response analysis of undamped SDOF bilinear system: (a) piece-wise linear time record; (b) power spectral density in decibel scale.

frequencies. The simulation of the breathing crack condition is conducted using a piecewise linear time record based on a bilinear stiffness model in a single degree of freedom (SDOF) system. The response time series and its spectral density are presented in Figure 1. The occurrence of high frequency harmonics at integer multiples of the fundamental frequency is attributed to nonlinearity caused by the breathing crack. However, this result does not give any indication of location of these harmonics in time space. Therefore, further investigation is conducted using DWT and CWT (see Figure 2).

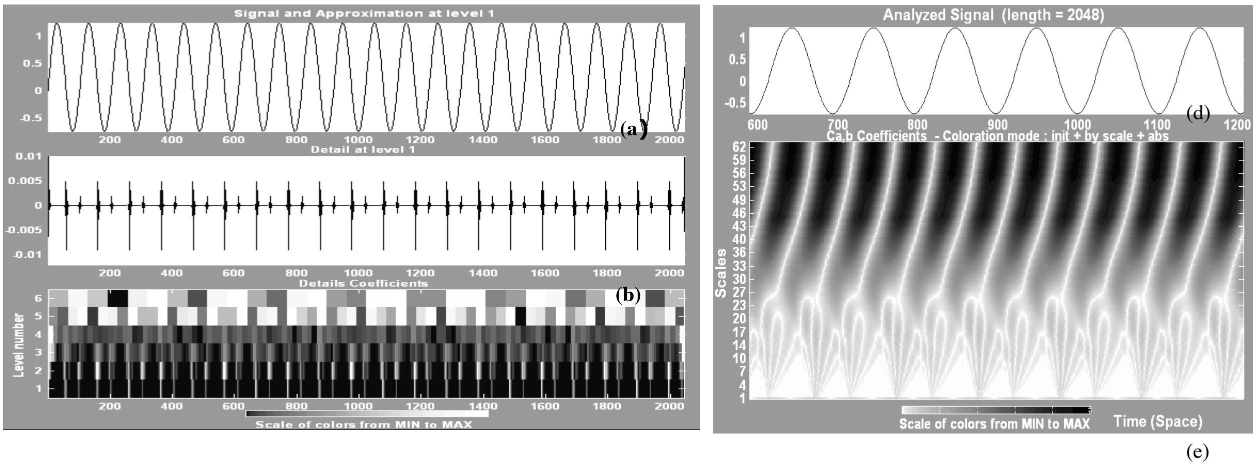

Figure 2 (i) DWT: (a) time series; (b) details at level 1; (c) details coefficients; and (ii) CWT (zoomed view): (d) time series; (e) CWT coefficients.

The details at level 1 of DWT conducted using Daubechies wavelet (db8) at level 6 show a series of spikes at the exact locations of the discontinuities; which is attributed to high frequency impulsive events at the crack interface due to the breathing crack condition (Figure 2 (b)). Moreover, the detail coefficients at the highest octave (level 1) provide the locations of the spikes and the consistent reduction in the ridge widths from higher to lower levels indicate the harmonics are the integer multiples of the fundamental frequency (Figure 2 (c)). Moreover, the CWT coefficients determined using db8 show a single ridge at higher scales (or lower frequencies) and multiple ridges at lower scales (or higher frequencies) which indicates the occurrence of higher harmonics breathing crack (Figure 2 (e)).

Identification of stiffness degradation in SDOF system

In this section, DWT is conducted on acceleration response data to detect and localize progressive stiffness degradation. First, inelastic dynamic analysis is performed on a SDOF system subjected to cyclic loading using a modified Takeda degrading stiffness hysteresis model (Figure 3 (a)). Second, DWT is conducted on the acceleration data using db8 at level 4 which clearly shows a series of spikes at level 1 details (Figure 3(b)). The locations of these spikes in time space are found to be in a close agreement with the stiffness history curve (Figure 3(c)).

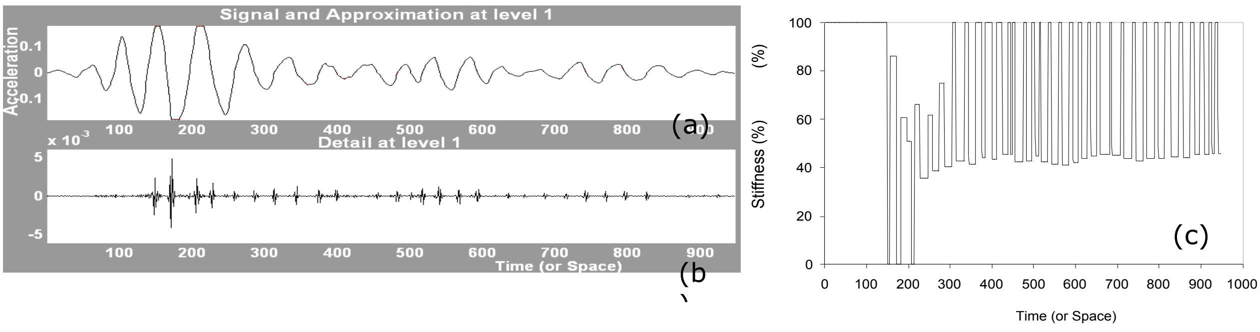

Figure 3 DWT of the acceleration response: (a) acceleration response; (b) details at level 1;

(c) stiffness time-history.

Case studies using earthquake records

Los Angeles 54-story building (LA54) subjected to 1994 Northridge earthquake

This study uses acceleration response records at 20 measurement points with a sampling interval of 0.01sec and a sampling length of 180 sec to produce 18001 data points per record as shown in Figure 4 (Ventura et al, 2001). First, modal parameters are extracted for the first 8 modes using the Enhanced Frequency Domain Decomposition (EFDD) option of the ARTeMIS Extractor® software (Table 1). Second, structural damage condition assessment is conducted using DWT of the acceleration record at the top of the building (ART) (Figure 5). The DWT tree for the 50 Hz signal is given in Table 2. Third, to look for any sign of nonstationarity for signal power and period with time and height of the building, the CWT is conducted using the Morlet wavelet on the acceleration record at the base of the building (ARB) and ART. Consequently, the WPS for both ARB and ART and the WCS and WCO between the ARB and ART were computed and presented in the time-period domain in Figure 6 and Figure 7, respectively.

(i) *Discussion on DWT Analysis*: The DWT details coefficients at level 1 of Figure 5 (b) show closely spaced short lived spikes which correspond to the higher frequency octaves. These observations clearly indicate impulsive and/or major rocking events that may have occurred during the early stage of the earthquake. Moreover, the detail coefficients in Figure 5 (c) reveal variations of the dominant modes for different frequency bands as shown by the dark color. At the early stage of the ground motion, transients and the clamped nature of the signal power were observed. This indicates that at early stage of the ground motion, the vibration response is mainly due to the higher frequency modes. However, the lower frequency components in levels 8 to 9 were largely stationary for most of the duration.

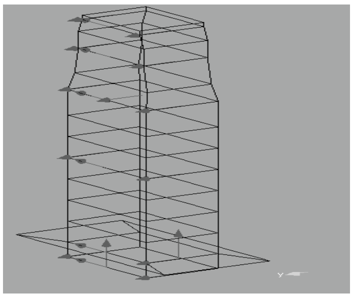

Figure 4 Building geometry and positions of transducers.

Table 1 Modal parameters of LA54 building

Mode No.	Frequency (Hz)	Period (sec)	Mode No.	Frequency (Hz)	Period (sec)
1	0.167	5.988	5	0.537	1.862
2	0.197	5.076	6	0.821	1.218
3	0.361	2.770	7	1.167	0.857
4	0.498	2.008	8	1.475	0.678

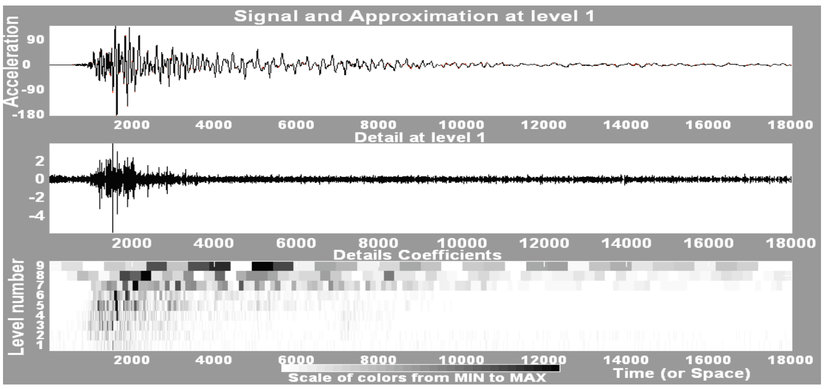

Figure 5 DWT of the Northridge Earthquake ART: (a) time series; (b) details at level 1; (c) details coefficients for different frequency bandwidths.

Table 2 DWT tree for 50 Hz

Level No.	Frequency bandwidth (Hz)
1	25-50
2	12.5-25
3	6.25-12.5
4	3.125-6.25
5	1.5625-3.125
6	0.781-1.5625
7	0.391-0.781
8	0.195-0.391
9	0.098-0.195

(ii) *Discussion on CWT Analysis*: The cone of influence shown by the parabolic curve in Figures 6 and 7 demarcate the boundary for edge effects, where any results below the curve are considered dubious. The dark grey color (or reddish in color format) enclosed with black contour lines represents the dominant power of the processes with 95% confidence level while the light grey color (or yellowish in color format) outside the contour line indicates moderate power and the rest show low power. Figure 6 (a) and (b) show common features as well as significant differences between the two power spectra in terms of the variations of high power with time and amplitude modulation across the height of the building. Figure 6 (b) indicates that during the intensive stage of the earthquake, the building response was mainly dominated by the higher frequency vibration modes and following the intensive shaking, the lower modes controlled the response of the structure. These results have significance in the context of wider application. For example, in the case of natural input experimental modal analysis, the assumption that the excitation is stationary is not so reasonable. Moreover, the appearance of time-varying signal power for ART has influence on the design of structures since earthquake excitation causes variations in response amplitudes and frequencies both within the time and space domains.

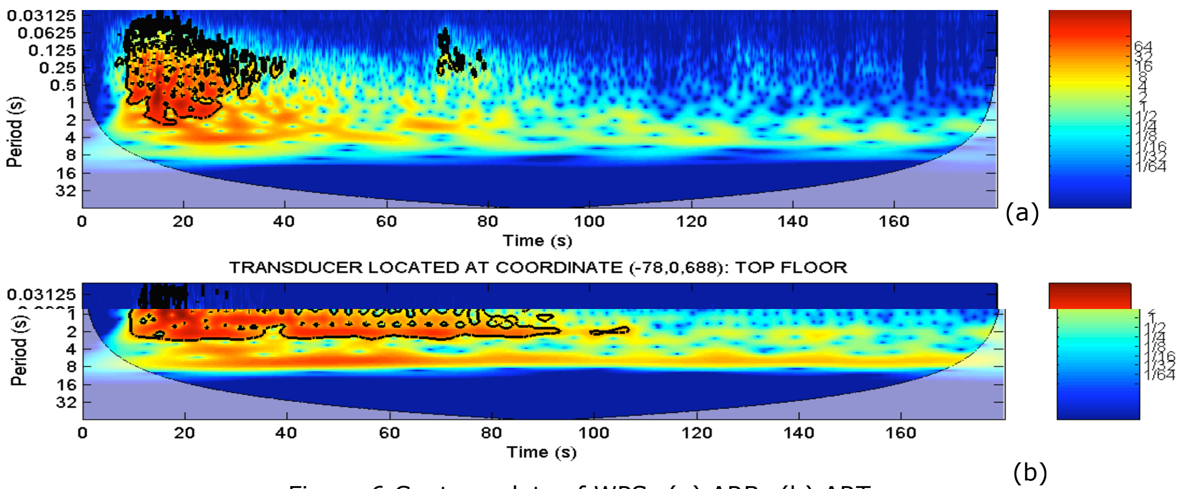

Figure 6 Contour plots of WPS: (a) ARB; (b) ART.

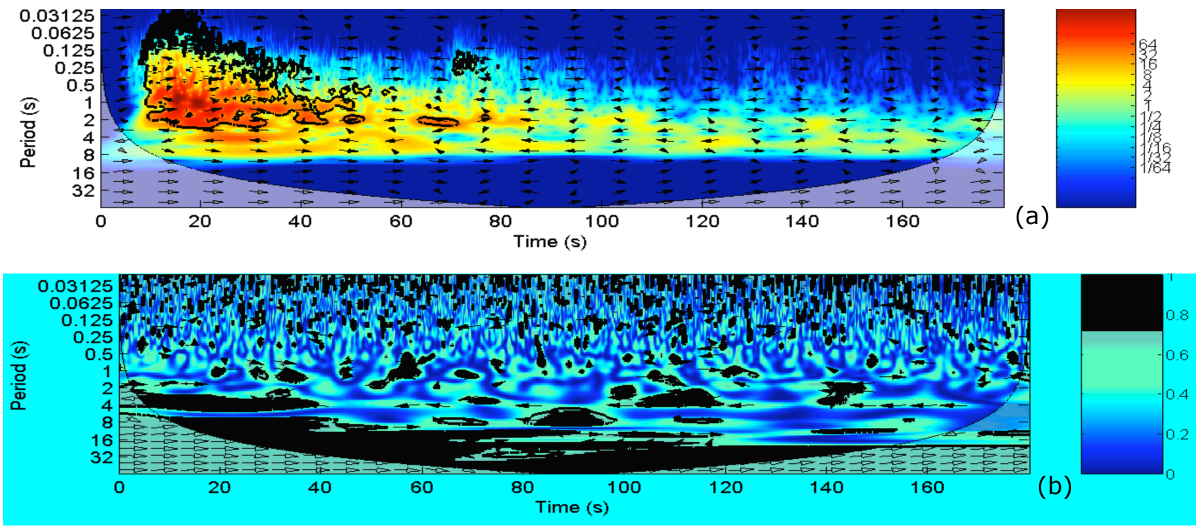

Figure 7 Contour plots of (a) WCS of the vibration data on the ground floor level against the top floor; (b) WCO between the vibration data on the ground floor level and top floor.

On the other hand, the WCS and WCO of ARB and ART are presented in Figure 7 (a) and (b), respectively. The relative phase relationship between the two processes is shown using arrows (where in-phase is pointing right, anti-phase is pointing left, ART leading ARB by 900 is pointing straight down). In Figure 7 (a) and (b), the light grey color (red in colored format) enclosed with black contour lines show areas of high common power and high coherence of the two processes at the 95% confidence level, respectively. While the WCS shows high common power at lower period bands of 0.125 to 2.75 seconds and at the early stage of the ground motion, WCO indicates negligible degree of correlation of the two processes at these locations. Instead, a significant coherence is observed for regions outside the area with significant common power and in the period bands of 1 to 8 seconds (Figure 7 (b)).

DWT of the ground motion records: Friuli earthquake M (6.4) and Imperial Valley earthquake in the 1940 at El Centro M (7)

The DWT of the Friuli and El Centro ground motion records are presented in Figure 8 (i) and (ii), respectively. The DWT results of the Friuli earthquake reveal the occurrence of stationary Gaussian white noise at high frequency band (Figure 8 (b) and (c)). This is evident from the property of the time trace at level 1 details, where the energy variation with time at level 1 of the detail coefficients is largely uniform (Figure 8 (c)). This shows that there is no sign of damage at this particular location during the Friuli earthquake. On the other hand, the DWT details of the El Centro ground motion record at level 1 show a series multiple spikes during the early stage of the ground motion (Figure 8 (e)). Figure 8 (f) also shows that these spikes correspond to the high frequency bandwidths or lower level details coefficients. Therefore, it can be concluded that there is enough indication to suggest progressive damage and/or that high energy impulsive events have occurred during the earthquake concerned.

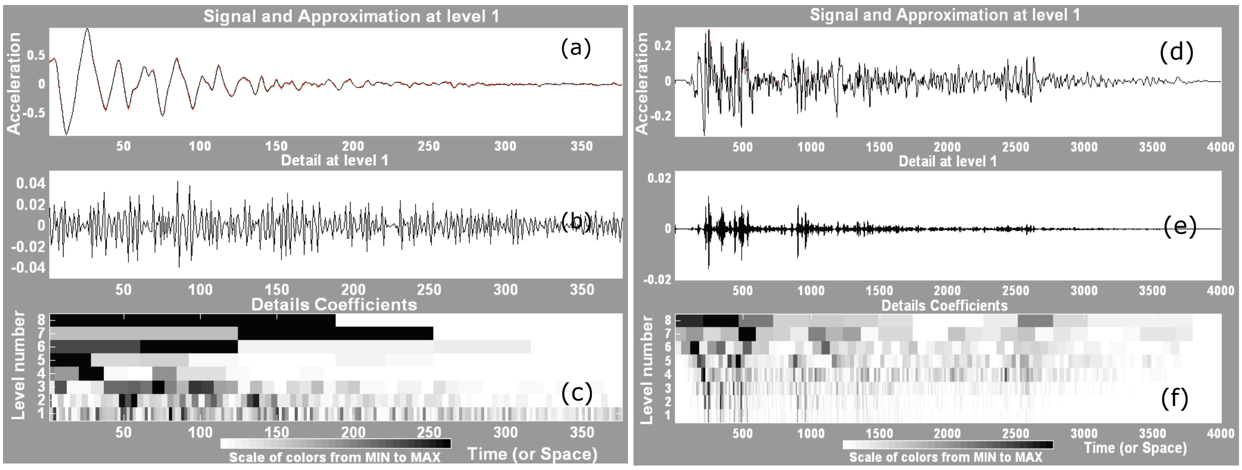

Figure 8 DWT of (i) Friuli earthquake: (a) time series; (b) details at level 1; (c) details coefficients; (ii) Imperial Valley earthquake at El Centro: (d) time series; (e) details at level 1; (f) details coefficients.

Conclusions

This paper presents wavelet analyses for condition assessment/damage detection after occurrence of extreme events by using earthquake ground motion records, directly. Unlike the Fourier transform, the wavelet analysis schemes adopted provide the capability to examine localized features of a larger signal through multiple levels of details and approximations of the original signal to determine the instantaneous changes in a real-time manner, including detection of sudden loss of stiffness, impulsive events due to breathing crack conditions, assessment of progressive cracking in structural mechanisms and differentiation of impulsive events from random noise. Moreover, features extracted from wavelet transforms were used to characterize the dominant modes of variations of power and frequency with time and space, including areas of significant high common power; phase relationship; and degree of correlation of the earthquake records at the base and top of a building.

Finally, the results and techniques presented in this study may contribute to development of post-earthquake integrity assessment strategy for in-service structures and for understanding structural response behavior when structures are subjected to nonstationary random processes.

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