

A harmonic vibration, output only and time-frequency representation based method for damage detection in Concrete piers of complex bridges

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doi:10.6088/ijcser.00202030025

ABSTRACT

Due to damage, vibrations of bridge piers compared with undamaged state would be changed. A new signal-based algorithm is proposed to extract feature and detect damage in complex bridges. According to the proposed algorithm, it is necessary to vibrate the bridge before and after damage by exciting force and record responses at the middle and top of the piers. For this purpose, sine and cosine transient forces were applied to the analytical model of Ghotour Bridge and the signals of pier responses were recorded. Using reduced interference distribution, the response signals were processed and time-frequency plans were calculated. Modified matrix subtraction method was proposed to detect damage. Based on the results, damage was identified and located with good accuracy. The proposed algorithm is an output-only method and in practice there is no need to create an analytical model of an existing complex bridge for damage detection.

Keywords: Feature identification, damage detection, time-frequency representation, bridge, modified matrix subtraction.

1. Introduction

For evaluation and assessment of the structural conditions of bridges, observational methods, nondestructive testing and static methods based on strain or displacement measurements under static loads and vibration based methods have been used. Vibration based methods of health monitoring are performed according to the changes in vibration and dynamic characteristics after damage happened. During the last two decades, many joint researches regarding vibration based methods have been done, leading to the development of various algorithms and techniques (Doebling et al., 1996, Sohn et al., 2003). These methods can be divided into modal and signals methods.

The signal methods are used in both time domain and frequency domain from linear and stationary signals, but bridges have nonstationary responses and their seismic responses are often influenced by their nonlinear behavior. Therefore, this study first time uses time-frequency domain based square time-frequency representation to extract and identify features of bridges. Square time-frequency representations are used in various fields including radar, image processing, biomedical engineering, geophysics, quantum mechanics, signal processing, mechanics and electronics (Boashash, 2003). Nevertheless, to our knowledge, no report has been published so far regarding the use of these representations for feature extraction and damage detection of the structural system of bridges.

For this purpose, we used the Ghotour railroad bridge model, which is in the direction of Iran-Turkey Railway and located near the town of Khoy (Iran). The bridge response signals were measured under the influence of harmonic loading in both safe and damaged cases, and processed by Reduced Interference Distribution. Then using modified matrix subtraction method, damage was detected.

In this paper we present a new algorithm based on square time-frequency representation (TFR) and modified matrix subtraction method to detect seismic damage in the bridge piers. The rest of this paper is organized as follows. In Section 2, the best TFR to process response signals of bridge piers and suitable lengths of time and frequency windows are briefly introduced according to (Daneshjoo et al., 2011). In Section 3, the well-known TFR methods and Reduced Interference Distribution are briefly reviewed. In Section 4, the new modified matrix subtraction method for damage detection is proposed. In Section 5, the damage detection methodology is explained. In the next Section, the introduced damage detection method and the modified matrix subtraction method are used to detect seismic damage of an existing nine-span steel arch railway bridge. Finally, Section 7 provides the research conclusions.

1.1 The Best TFR to Process Response Signals of Bridge Piers

Based on the signal methods, changes in the structural characteristics are obtained directly from the measured time histories. Signal procedures are divided into three categories: time domain methods, frequency domain methods and time–frequency methods. In both the time domain and frequency domain methods, typically stationary and linear signals must be used. For example, Auto-Regressive model can be used for stationary signals, and if it be used for nonstationary signals, estimation of AR parameters will be difficult (Cheng et al., 2008). Auto-Regressive Moving Average model often is used for stationary signals (Bonato et al., 1998, De Stefano et al., 2001). If this method is used for nonstationary signals, computing time increases (De Stefano et al., 2001). In addition, only when the time-dependent ARMA model is applied to the commonly linear frequency and amplitude modulated signals, can be processed satisfactorily (Cheng et al., 2008).

Most of the frequency-domain methods such as frequency response functions (FRFs) and power spectral density (PSD) are based on Fourier Transform. Fourier Transform is used to calculate the signal frequency content, but it cannot determine when the frequency components have occurred (Melhem and Kim, 2003, Neild et al., 2003, Wang and Chen, 2011). In other words, Fourier Transform is appropriate for processing those signals that their frequency content does not change with time. However, if the signal frequency content varies with time, Fourier Transform cannot provide a complete assessment of the system behavior (Neild et al., 2003). Using Fourier Transform, the frequency content of signal as a set of weighted sinusoidal functions is determined but other important information such as changes in signal characteristics cannot be identified. Due to the limitations, some other methods have recently been suggested that are able to process signals in time domain and frequency domain simultaneously (Bradford, 2006). Principles of TFR have been established many years ago but to our knowledge, there is no recent published on the use of square TFRs for feature extraction and system identification and especially damage detection of bridges. In this study, the use of square TFR is proposed to extract the dynamic characteristics of bridge structures. Civil engineering structures usually have nonstationary responses, and seismic responses are affected by the nonlinear behavior of structures (Bradford, 2006, Qiao, 2009). The main advantage of using TFRs is that these functions can process all signals such as stationary,

nonstationary and nonlinear (Zhang et al., 2003, Bonato et al., 1998, Bonato et al., 2000, Qiao et al., 2009, Zou and Chen, 2004, Peng et al., 2005, Epasto et al., 2010). Often identification of the signal characteristics with a time domain graph is difficult. However, by using time-frequency analysis, another axis is added to the signal graph, and frequency axis with respect to time axis (or vice versa) is plotted accordingly.

To identify the best square TFR to process the response signals of bridge piers, comprehensive study has been done by the authors (Daneshjoo et al., 2011) and finally, the Reduced Interference Distribution (RID) has been chosen as the desired function. Six representations, including spectrum of Short Time Fourier Transform (Spectrogram), Spectrum of Wavelet Transform (Scalogram), Wigner-Ville Distribution, Choi-Williams Distribution, Smoothed Pseudo Wigner-Ville Distribution and Reduced Interference Distribution with Hanning kernel have been comprehensively studied and the results have been compared in (Daneshjoo et al., 2011) and therefore, in this study, RID with Hanning kernel has been used to process bridge responses.

Also in order to determine the lengths of time and frequency windows, an extensive study has been conducted by the authors and finally, the suitable composition for time and frequency windows has been calculated (Daneshjoo et al., 2011). Accordingly, the length of time window equal to one-tenth of the samples and the length of frequency window equal to one quarter of the samples are suitable to process the response signals of bridge piers by TFRs. TFRs express a time series in the form of three dimensional diagram including changes in frequency content with respect to time. TFRs provide the opportunity that the energy of the signal is visible in both the time and the frequency domains simultaneously.

2. Reduced Interference Distribution (RID)

RID have some advantages compared with Wigner-Ville Distribution (WVD). WVD is the most basic method in square time-frequency representations. Many other time-frequency representations (like Spectrogram or Scalogram) can be gained of WVD with an appropriate choice of smoothing factors. For an analytic signal, WVD is defined as follows (Boashash, 2003):

$$WVD_x(t, \omega) = \int_{-\infty}^{\infty} x(t + \tau/2) x^*(t - \tau/2) e^{-i\omega\tau} d\tau \quad (1)$$

where, t and ω are time and angular frequency, respectively. $x(t)$ is analytical signal and $*$ indicates the complex conjugate. Analytical signal is defined as follows:

$$x(t) = s(t) + jH[s(t)] \quad (2)$$

where, $s(t)$ is the real signal and $H(t)$ is the Hilbert Transform. Hilbert Transform is described as below (Mertin, 1999, Boashash, 2003):

$$H[s(t)] = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{s(\tau)}{(t - \tau)} d\tau \quad (3)$$

in which, PV indicates the Cauchy principle value.

Both RID and WVD are in Cohen's class. However, RID is more suitable for transient and nonstationary signals. The equation of RID is below (Boashash, 2003, Neild et al., 2003):

$$RID(t, \omega) = \int_{-\infty}^{+\infty} h(\tau) R_x(t, \tau) e^{-i\omega\tau} d\tau \quad (4)$$

$$R_x(t, \tau) = \int_{-\frac{\tau}{2}}^{+\frac{\tau}{2}} \frac{g(v)}{|\tau|} \left(1 + \cos \frac{2\pi v}{\tau} \right) x \left(t + v + \frac{\tau}{2} \right) x^* \left(t + v - \frac{\tau}{2} \right) dv \quad (5)$$

where, $h(\tau)$ is time smoothing window and $g(v)$ is frequency smoothing window.

In this study Hanning window was used to estimate the spectrum of time-frequency representation as follows:

$$Hann(v) = \frac{1}{2} + \frac{1}{2} \cos \left(\frac{2\pi v}{\tau} \right) \quad (6)$$

2.1 Proposed Modified Matrix Subtraction Method

Using TFRs, signal energy can be seen in both the frequency domain and time domain simultaneously. Damage has a direct relation with energy balance in the structure. Thus, if a signal energy distribution can be calculated in the frequency domain and time domain simultaneously, this distribution can be correlated with the severity, the location and the time of the damage event. For $RID(t, \omega)$, instantaneous energy $|x(t)|^2$ and energy density spectrum $|S(\omega)|^2$ are defined as equations 7 and 8, respectively (Cohen, 1989).

$$|x(t)|^2 = \int_{-\infty}^{+\infty} RID(t, \omega) d\omega \quad (7)$$

$$|S(\omega)|^2 = \int_{-\infty}^{+\infty} RID(t, \omega) dt \quad (8)$$

And the total energy of signal is calculated as follows:

$$E = \int_{-\infty}^{+\infty} RID(t, \omega) d\omega dt \quad (9)$$

In this study, a new algorithm has been proposed to detect damage named as “modified matrix subtraction method (MMS)”, which is a simple but practical method. The basic idea of this method is derived from the references (Beskhyroun et al., 2005, Beskhyroun et al., 2010, Mikami et al., 2011). In the references, the basic proposed method for damage detection is based on that the structure’s responses are converted from the time domain to the frequency domain by using power spectral density function. Using the structure’s response at various measuring points and applying a cubic polynomial function, operational mode shapes at each frequency component are calculated. Then the mode shapes are decomposed using Discrete Wavelet Transform (DWT) to desired decomposition level. Finally, the difference between the DWT approximation coefficients before (G1) and after (G2) damage is used to identify the possible damage location.

$$\Delta_l^i(f) = |G1_l^i(f) - G2_l^i(f)| \quad (10)$$

where, i , l and f are DWT approximation component, measuring points number and frequency value, respectively.

Accordingly after calculating DWT approximation components for a set of operational mode shapes, a matrix Δ^i can be defined as:

$$\Delta^i = \begin{bmatrix} \Delta_1(f_1) & \Delta_2(f_1) & \dots & \Delta_n(f_1) \\ \Delta_1(f_2) & \Delta_2(f_2) & \dots & \Delta_n(f_2) \\ \vdots & \vdots & \ddots & \vdots \\ \Delta_1(f_m) & \Delta_2(f_m) & \dots & \Delta_n(f_m) \end{bmatrix} \quad (11)$$

where, n is the number of measuring points. To detect the damage location, Total-Change indicator was defined as follows:

$$Total - Change = \sum_{i=1}^j \sum_{f=f_1}^{f_m} \Delta_l^i(f) \quad (12)$$

In this study, according to square TFR, some modifications have been induced to the method. In fact, due to the ability of TFR, besides the frequency dimension, time dimension has also been added to the matrix subtraction method.

When damage is occurred in the bridge piers, the bridge's response signals are changed compared with the intact state. Therefore, time-frequency plans related to the signals should be different before and after the damage. So it seems that it is possible to detect damage by checking these differences. For this purpose, the matrices of time-frequency plans when the bridge structure is undamaged (TF_S) and when it is damaged (TF_D) are calculated as follows, respectively:

$$TF_S = \begin{bmatrix} RID_S(t_1, f_1) & RID_S(t_1, f_2) & \dots & RID_S(t_1, f_n) \\ RID_S(t_2, f_1) & RID_S(t_2, f_2) & \dots & RID_S(t_2, f_n) \\ \vdots & \vdots & \ddots & \vdots \\ RID_S(t_m, f_1) & RID_S(t_m, f_2) & \dots & RID_S(t_m, f_n) \end{bmatrix} \quad (13)$$

$$TF_D = \begin{bmatrix} RID_D(t_1, f_1) & RID_D(t_1, f_2) & \dots & RID_D(t_1, f_n) \\ RID_D(t_2, f_1) & RID_D(t_2, f_2) & \dots & RID_D(t_2, f_n) \\ \vdots & \vdots & \ddots & \vdots \\ RID_D(t_m, f_1) & RID_D(t_m, f_2) & \dots & RID_D(t_m, f_n) \end{bmatrix} \quad (14)$$

where, n is the number of frequency bins and m is the time instants.

The number of components of the time-frequency matrix corresponds with the time instants of recorded bridge responses. In the study, the bridge responses were sampled at 0.01 second increments. Thus the number of the rows of time-frequency matrices equal to the time length of the exciting forces is divided by 0.01. In addition to increase the resolution of time-frequency plans and accuracy in damage detection, the number of columns has been considered equal to the number of rows.

$$\Delta(i, j) = TF_S(t_i, f_j) - TF_D(t_i, f_j) \quad (15)$$

In the Δ matrix, each component represents the difference between the time-frequency plan matrices. Overall, the difference in frequency bins and time instants can be estimated with the sum of Δ matrix components as follows:

$$Difference = \sum_{i=1}^m \sum_{j=1}^n |\Delta(i, j)| \quad (16)$$

If the pier is undamaged, the Difference will be near zero or zero. The Differences were calculated in the middle and high levels of the piers and normalized at every level based on the larger number. Finally, by comparison of the results obtained, the damaged pier was identified.

2.2 Proposed Damage Detection Methodology Using MMS Method

The main hypothesis of this study is based on the fact that the damage at the pier of bridge will disturb the dynamic responses near its location. The differences between the dynamic responses of a bridge, before and after damage, often cannot be determined from the registered signals but if the signals are processed by TFRs, most probably the differences will be revealed.

According to the algorithm, an excitation force is applied to a bridge before and after earthquake occurrences and its responses at the piers are registered. However, there is no need to record the excitation force (input loading). In addition, this algorithm, unlike many other methods, needs not to create an analytical model of the bridge. In this study, since there was no possibility of creating damage in the real bridge, the analytical model of the real bridge has been used. For this purpose, the bridge model has been excited by two low amplitude exciting forces. The first is a sine function with angular frequency equal to $2\pi/3$ (Figure 1). The second is composed of 5 sections, including three cosine functions and two transient cosine functions (Figure 2).

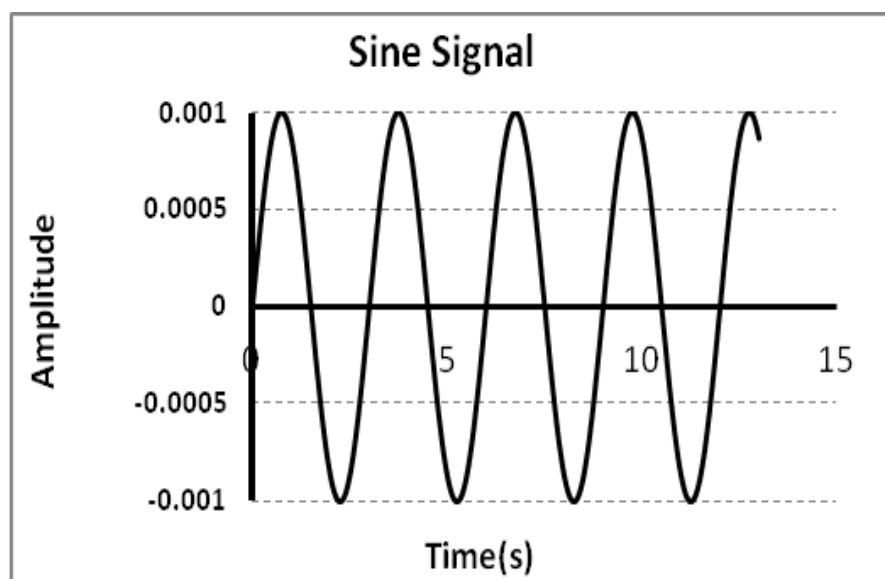


Figure 1: The first exciting force

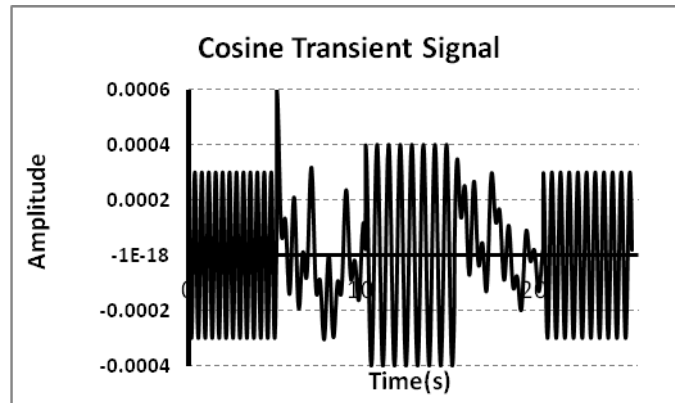


Figure 2: The second exciting force

To calculate the bridge model responses under exciting forces, the model has been analyzed based on the linear time history method, and its responses have been measured at the middle and top of the piers. On the other hand, to record the bridge responses, accelerometers have been installed in the middle and top of the piers.

If the bridge piers have differences in height and section, to decrease the effect of pier height, to integrate response signals of bridge piers and to generalize the proposed method for all bridges, the response signals must be normalized. On the other hand, the response signals of every bridge pier were divided into the length of that pier.

3. Confirmation of proposed MMS Method and Methodology

To evaluate MMS method and proposed methodology, Ghotour railway bridge, which has significant size and complexity was selected as the structural sample. In the following subsections, firstly Ghotour railway bridge is introduced and the destructive tests which have been performed on the steel and concrete used in the bridge, are explained. Furthermore, the analytical model of Ghotour railway bridge is described. Then, four boreholes which have been drilled to study the geological conditions at the bridge site are explained. In addition, selected ground motions that were used for nonlinear dynamic analysis are introduced and time history analysis results briefly discussed. Then, according to the proposed methodology, bridge responses under excitation forces are registered and their features are extracted. Moreover, for pattern recognition and damage detection, MMS method was used.

3.1 Ghotour Railway Bridge and Its Analytical Model

Ghotour railway bridge, with 448 meter length and the height from the surface of Ghotour river of 118.28 meters, has been built in the northwest Iran on the Ghotour river. The bridge is located in a region with $44^{\circ}46'30''$ longitude and $38^{\circ}29'30''$ latitude in the range of West Azerbaijan province. One of its spans is made of steel truss as low arch with the length of over 223 meters. Totally, including this span, the bridge has 9 spans, and the other spans are made of concrete piers or abutments. The bridge deck is made of steel. Figures 3 and 4 show a side view of the bridge and its analytical model, respectively.

The steel and concrete used in the bridge were tested by Iran's Railway Company in 2008. For this purpose, 10 concrete samples have been removed from the piers and abutments, and

12 steel samples have been removed from the deck and the arched span (TTSDIR, 2008). Figures 5 show extracting a concrete sample from the pier. In addition, 3 samples of the bars used in the piers have been removed and tested (TTSDIR, 2008). Using the results of compressive strength testing of the concrete samples, and tensile testing of the steel and the bar samples, the average compressive strength of concrete, the average yielding stress and the average ultimate stress of steel samples have been calculated. The results are shown in Table 1. In addition, current condition, member sizes, connections and support bearings of the bridge have been assessed and evaluated by in-situ measurements (Figure 6).

The bridge model has 1686 nodes, 2362 frame elements and 502 solid elements. The model was analyzed with regard to the gravity loads. The first 20 Eigen periods of the bridge are given in Table 2. Modal analysis was performed according to the Eigen Vector method.



Figure 3: A side view of Ghotour railway bridge

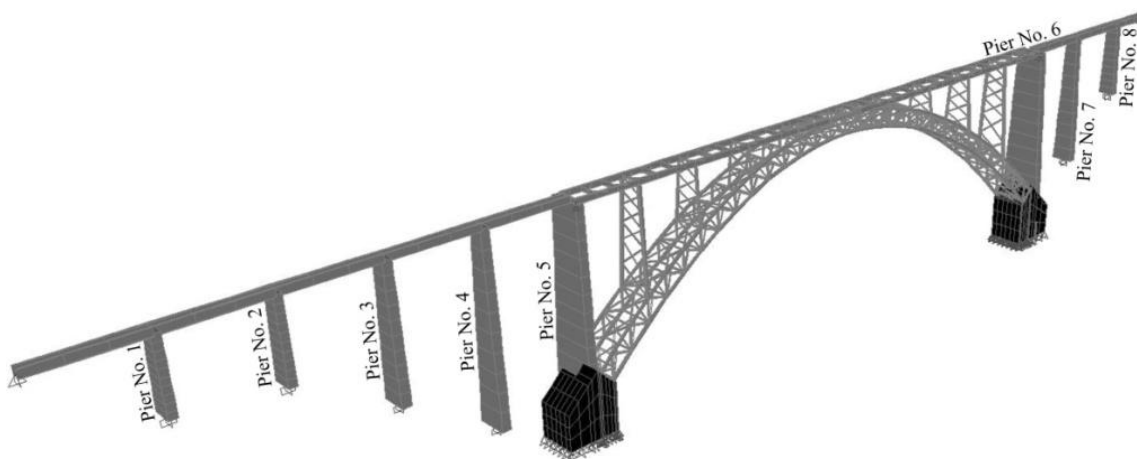


Figure 4: Analytical model of Ghotour railway bridge

Table 1: Test results of the strength of materials used in Ghotour railway bridge

Ultimate stress of steel (MPa)	Yielding stress of steel (MPa)	Compressive strength of concrete (MPa)	Material	Row
-	-	26.2	Concrete	1
434.8	288.5	-	Steel (deck and arched span)	2
597.8	386.3	-	Steel (bar)	3



Figure 5: Extracting a concrete sample from a pier of Ghotour railway bridge



Figure 6: Preparing as built plan of Ghotour railway bridge

3.2 Ghotour Bridge Seismic Vulnerability Assessment

To assess the seismic vulnerability of Ghotour bridge, first, the geological conditions at the bridge site were studied. For this purpose, four boreholes were drilled at the bridge location using the rotational method by Iran's Railway Company.

To study the samples, various tests were performed. Based on the findings of studies on the achieved samples from drilling and extraction, the selected ground motions that were used to assess the seismic vulnerability of Ghotour bridge must be recorded on the class A of site classification. Accordingly, Kocaeli, Northern Calif and Whittier Narrows records were selected to perform the nonlinear time history analysis and assess the seismic vulnerability of

the piers of Ghotour bridge. The ground motions are far field, and the location where they have been recorded is according to the site classification of Ghotour bridge. Properties of the records could be found in Table 3, and their Fourier Transforms are shown in Figures 7, 8 and 9.

Table 2: Eigen periods of the analytical model of Ghotour railway bridge

Mode num.	Period (s)	Frequency (cyc/sec)	Circle frequency (rad/sec)
1	1.918362	0.52128	3.2753
2	1.46494	0.68262	4.289
3	1.031117	0.96982	6.0936
4	0.799128	1.2514	7.8625
5	0.742012	1.3477	8.4678
6	0.69744	1.4338	9.0089
7	0.69415	1.4406	9.0516
8	0.693242	1.4425	9.0635
9	0.681799	1.4667	9.2156
10	0.666516	1.5003	9.4269
11	0.645825	1.5484	9.7289
12	0.641672	1.5584	9.7919
13	0.550389	1.8169	11.416
14	0.544997	1.8349	11.529
15	0.541602	1.8464	11.601
16	0.536634	1.8635	11.709
17	0.53235	1.8785	11.803
18	0.489681	2.0421	12.831
19	0.485791	2.0585	12.934
20	0.471649	2.1202	13.322

Table 3: Characteristics of the ground motions applied to Ghotour railway bridge model

PGA (g)	Record Station	Event Time	Record Name	Row
0.115	Cape Mendocino	1975	Northern Calif	1
0.186	MT Wilson	1987	Whittier Narrows	2
0.244	Gebze	1999	Kocaeli	3

In addition, according to the geological and geotechnical researches and studying the local faults, a probabilistic seismic hazard analysis was done by Track & Technical Structures Department of Iran Railways (TTSDIR) and site-specific design spectrum for two hazard levels were calculated. Hazard level 1 was determined based on 10% earthquake probability of exceedance in 50 years where the return period equals 475 years and hazard level 2 was determined based on 2% earthquake probability of exceedance in 50 years where the return period equals 2475 years. With regard to the site-specific spectrum, peak ground acceleration (PGA) corresponding to 475 year return period, was calculated as equal to 0.46g. Therefore, all the three ground motion records were scaled based on 0.46g.

The most appropriate method, which can be used for the structural analysis, is the nonlinear dynamic procedure (Ghodrati Amiri et al., 2009). According to (Elnashai, 2002), unlike the static inelastic analysis that is ever decreasing, nonlinear dynamic analysis is the “necessity domain”. In this method, the main goal is actually solving the Equation 17 (differential equation of dynamic equilibrium of motion):

$$m\ddot{v}(t)+c\dot{v}(t)+kv(t)=p(t) \quad 17$$

where, m , c and k are the mass, damping and stiffness matrixes, respectively, $v(t)$ is the dynamic response and $p(t)$ represents the effective load acting on the system (Clough and Penzin, 2003).

The ground motion records were applied to the finite-element model of Ghotour bridge. Nonlinear dynamic analysis is done in two general methods consisting of Direct Integration and Modal Analysis (Bathe, 1996). To determine the dynamic response of the bridge to the earthquake loading and solving the dynamic equilibrium equations of the bridge motion, nonlinear time-history analysis with direct integration was used. To perform direct integration time-history analysis, Newmark method was applied. Furthermore, viscous damping was used through defining mass and stiffness proportional components. During the time history analysis, $P-\Delta$ effects were considered as well.

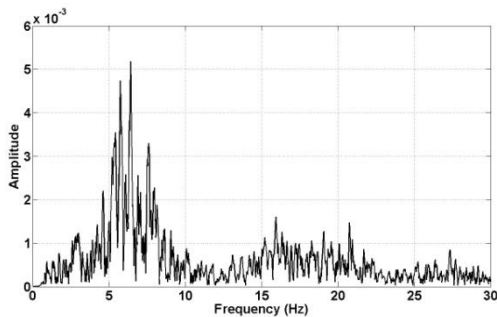


Figure 7: Fourier Transform of Northern Calif

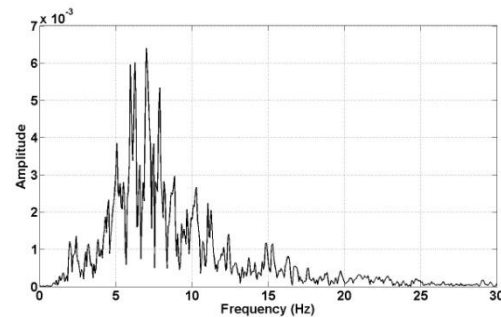


Figure 8: Fourier Transform of Whittier

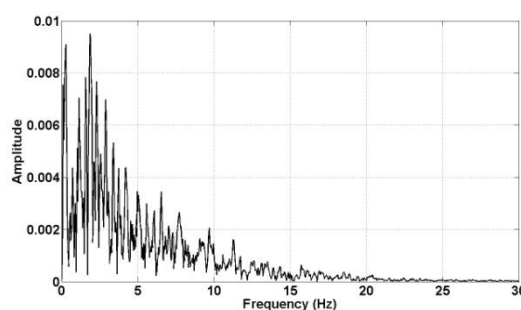


Figure 9: Fourier Transform of Kocaeli

Based on the results of nonlinear time history analysis, under Northern California ground motion, no pier was damaged. In addition, under Whittier Narrows ground motion, the plastic hinge was formed in the piers No. 1 and 2 but pier No. 1 was damaged. Furthermore, the plastic hinges were formed in the some of the piers under Kocaeli ground motion but pier No. 1 was more damaged. Finally, according to the calculated results, piers No. 1 was found to be the most vulnerable in comparison to the other piers. The seismic damages were assessed and

evaluated, and to apply them, the stiffness in the bottom of the pier No. 1 was reduced by about 30%.

3.3 Feature Extraction

As already mentioned, in this study a new algorithm is suggested to seismic damage detection in the piers of bridges. Based on the algorithm, two excitation forces including sine and Cosine Transient force were applied to the analytical model, before and after happening the earthquake and its responses at the piers are registered. The responses were processed and related time-frequency plans were calculated. The three-dimensional diagrams of time frequency plans related to the response signals of the top of the pier No. 1 are shown in figures 10 and 11.

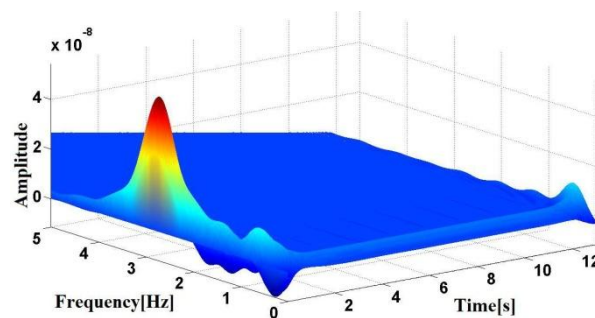


Figure 10: Time-frequency plan of RID affected by sine signal

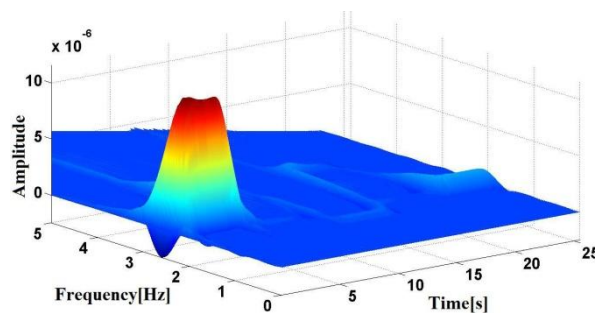


Figure 11: Time-frequency plan of RID affected by cosine transient signal

3.4 Damage Detection

Now using the calculated time-frequency plans, the performance of the method can be evaluated. The calculation results are shown in figures 12 and 13.

As shown in figures 12 and 13, under the effect of two exciting forces, the probability of the existence of damage in pier 1 is equal to 100%. In addition, the probability of the existence of damage in most of the other piers has been calculated as equal to small values or zero. Based on the recorded responses at the top of the piers, maximum error in determining the location of the damage is 14% and 15% in sinusoidal and transient loads, respectively. Furthermore, according to the recorded responses at the middle of the piers, maximum error is also 28% and 30% in sinusoidal and transient loads, respectively.

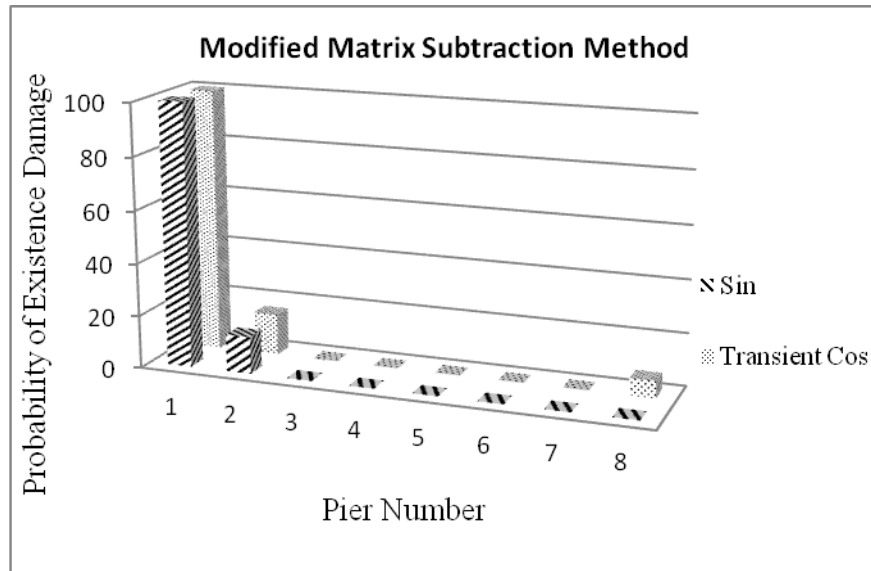


Figure 12: Damage diagnosis diagram based on the recorded responses at the top of the piers using modified matrix subtraction method

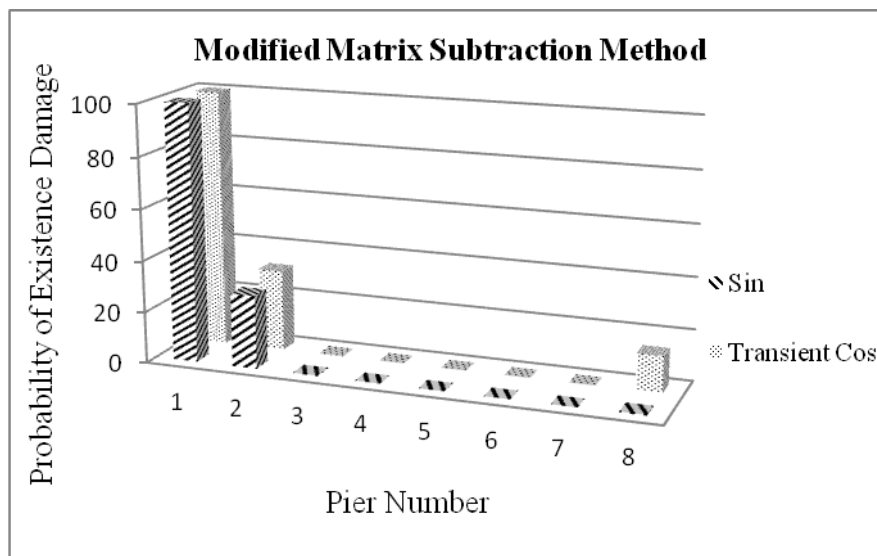


Figure 13: Damage diagnosis diagram based on the recorded responses in the middle of the piers using modified matrix subtraction method

Accordingly, it is clear that the proposed algorithm has presented very good performance in damage detection and generally, in identification of damage location.

4. Conclusion

A new algorithm was proposed to detect damage in bridge piers. For the first time, damage in the concrete pier of a bridge is determined by square TFR and MMS method. MMS is an applied method based on square TFR that is able to detect damage and identify its location. RID function was used to process response signal of bridge piers.

To evaluate the proposed algorithm, Ghotour bridge, which has significant size and complexity, was selected as the structural sample. To create the finite-element model according to the current condition of the Ghotour railway bridge, extensive in-situ and laboratory measurements were performed by TTSDIR. In addition, some boreholes were drilled in the bridge's construction site. The probabilistic seismic hazard analysis was done by TTSDIR and site specific design spectra were calculated for two hazard levels.

As already mentioned, the proposed approach does not need numerical model for system identification and damage detection. Moreover, the algorithm could detect damage in the concrete pier of Ghotour railway bridge precisely. In addition, the algorithm needs not to measure the input force. In fact, this algorithm can extract the dynamic properties of the bridge and detect any possible damage only based on the measured response of bridge structures. Therefore, considering the simplicity of the proposed algorithm, it can be used in health monitoring of bridges.

Acknowledgment

The authors gratefully acknowledge all the assistance provided by the Track and Technical Structures Department of Iran Railways for this research. We especially appreciate Eng. G. Mobtaker for his kind help to provide experimental data.

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