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# Application of power spectral density function for damage diagnosis of bridge piers

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**Abstract.** During the last two decades, much joint research regarding vibration based methods has been done, leading to developing various algorithms and techniques. These algorithms and techniques can be divided into modal methods and signal methods. Although modal methods have been widely used for health monitoring and damage detection, signal methods due to higher efficiency have received considerable attention in various fields, including aerospace, mechanical and civil engineering. Signal-based methods are derived directly from the recorded responses through signal processing algorithms to detect damage. According to different signal processing techniques, signal-based methods can be divided into three categories including time domain methods, frequency domain methods, and time-frequency domain methods. The frequency domain methods are well-known and interest in using them has increased in recent years. To determine dynamic behaviours, to identify systems and to detect damages of bridges, different methods and algorithms have been proposed by researchers. In this study, a new algorithm to detect seismic damage in the bridge's piers is suggested. To evaluate the algorithm, an analytical model of a bridge with simple spans is used. Based on the algorithm, before and after damage, the bridge is excited by a sine force, and the piers' responses are measured. The dynamic specifications of the bridge are extracted by Power Spectral Density function. In addition, the Least Square Method is used to detect damage in the bridge's piers. The results indicate that the proposed algorithm can identify the seismic damage effectively. The algorithm is output-only method and measuring the excitation force is not needed. Moreover, the proposed approach does not need numerical models.

**Keywords:** moment-rotation; forecasting; extreme learning machine; precast beam-to-column connection; partly hidden corbel

## 1. Introduction

The use of vibration-based damage identification methods has increased steadily in the past few decades (Masciotta *et al*. 2016, Ahmadi *et al*. 2018). There are lots of new approaches has been developed in design procedures of the structures. It is desirable to find the optimum inputs to obtain the best performance of the system (or output). In Meymian *et al*. (2018) used FEM along with a neural network algorithm to find the optimum design parameters of an structure which resulted in the desired target natural frequency of the structure and reduced probability of fatigue failure. Nabizadeh *et al*. (2018) studied and applied the survival analysis of bridge superstructures in Wisconsin. Survival analysis techniques can provide such a global probabilistic model given availability of large-scale data. Conventional methods for structural damage detection consist of observational and non-destructive Evaluation (NDE) methods. For example, the observational method relies on an expert checking the appearance of cracks in structures. Non-destructive methods use computed tomography, laser scanning, ultrasonic and acoustic methods. These approaches are most suitable for local damage detection. However, the weakness of this method is evident especially in large and complicated structures in invisible or closed environments. In addition, structures need to be checked locally, which can be very time consuming (Masciotta *et al.* 2016). Usually, bridges are built over natural barriers such as valleys and rivers or man-made barriers such as roads and railroads. Because of these obstacles, bridge inspection is associated with danger and difficulty. Although small bridges can be inspected with a ladder, boat or other simple types of equipment, large bridges or high-altitude bridges are not easily available. In other words, in civil engineering, non destructive methods and observational inspections are very common, but they are time-consuming and laborious (Yan *et al.* 2005, Ahmadi *et al.* 2015). Considering the difficulties and shortcomings of the methods, vibration-based methods as a global way to evaluate the structural condition are expanding (Zhang *et al.* 2014).

Generally, health monitoring and damage detection methods consist of two main processes that are called feature extraction and pattern recognition. Various methods

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for feature extraction and pattern recognition have been proposed by researchers. During the last two decades, many joints research regarding vibration based methods has 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 modal methods use measured changes in modal parameters to detect damage. The methods have been applied to determine the dynamical properties of structural systems (Najafabadi *et al.* 2018). Changes in the modal shapes are a well-known technique in modal methods. Although modal methods can generally be used for health monitoring and damage detection, signal methods in comparison with modal methods are more efficient and are used in various fields such as mechanical engineering, aerospace engineering, and civil engineering (Qiao 2009, Bayat *et al.* 2015, Shao *et al.* 2017, Walia *et al.* 2015, Jorquera *et al.* 2016, Lee *et al.* 2016, Yang *et al.* 2018, Du *et al.* 2019, Nabizadeh 2015, 2018, Tabatabai *et al.* 2016, Kia *et al.* 2016, 2017, Duran *et al.* 2018, Sakka *et al.* 2018, Liu *et al.* 2017, Yin *et al.* 2016, Kutanaei *et al.* 2015, 2016, 2019).

In signal-based methods, changes in the structural characteristics are directly obtained from the measured time histories. According to various signal processing techniques, signal-based methods are classified into three categories: time domain methods, frequency domain methods and time–frequency domain methods. Structural engineers are familiar with the basic concepts of frequency domain, such as natural frequency and mode shapes. Because of this, and also with regard to capability and applicability of frequency domain methods, they have been widely used to diagnose damage in structures. Researchers have proposed several frequency domain methods that use modal data such as natural frequency ( Kimet *et al.* 2003, Pau *et al.* 2011), mode shape (Cornwell *et al.* 1999, Li *et al.* 2008), strain mode shape (Yan *et al.* 2012, Liu *et al.* 2014) , mode shape curvature (Wahab *et al.* 2001, Sazonov *et al.* 2005), response power spectra (Tang *et al.* 2011, Zhang *et al.* 2012, Yan *et al.* 2012), frequency response function ( Rahmatalla *et al.* 2012, Pradhan *et al.* 2012, Bernal *et al.* 2009), flexibility matrix (Zheng *et al.* 2015) and power spectral density (Gallego *et al.* 2015). However, the use of frequency domain methods can be very appropriate to identify damage in structures (Gallego *et al.* 2015).

Despite the many studies that have been done on damage detection methods, the existing methods still have problems and defects in detecting damage and identifying its locations. This is particularly difficult in large and complex structures. Another challenge to identify damage in civil engineering structures is the number of sensors to measure the responses. Usually, the number of sensors is subject to constraints, and therefore the recording of structural responses is accompanied by problems. Many civil structures have hundreds and even thousands of degrees of freedom (DOFs), while, in practice, due to limitations, only a small number of them can be registered. However, providing methods that can identify and locate damage with the minimum number of sensors is very important.

In this research, a novel algorithm and damage index for concrete piers of bridges are derived. Based on this simplified algorithm, the power spectral density function is used to process structural responses. Then, using the information obtained from the system identification, the damage is identified and its location in the piers is detected. To diagnose the damage, a new damage index is proposed based on the least square distance. The numerical model of W180 bridge is used to demonstrate the efficacy of the proposed methods. The calculated results show that the proposed algorithm and also damage index are able to accurately detect, and locate the damage_ in bridge piers. An important feature of the algorithm is its simplicity and applicability. Meanwhile, damage detection is only done using a sensor in each of the piers. Not needing to measure the exciting loads along with creating the analytical model of the bridge, are other advantages of the proposed algorithm.

The modal amplitude for each frequency is closely dependent to its spectral density or power spectral density (PSD). The power spectral density explains the distribution of power considering frequency. It is calculated by the Fourier transform of the autocorrelation function. The autocorrelation function for analytical signal x(t) is defined as (Stoica *et al.*2005 ) :

$$r_{xx}(t_1,t_2)=\varepsilon\left\{x^*(t_2)x\left(t_1\right)\right\} \tag{1}$$

herein, * indicates complex conjugation and ε{…} denotes the expected value. Generally, the autocorrelation function denotes how similar the process is at times $t_1$ and $t_2$.

However, PSD of the signal can be written as (Havelock *et al.* 2008) :

$$S_{xx}(\omega)=\int_{-\infty}^{\infty} r_{xx}(\tau)e^{-j\omega\tau}d\tau \tag{2}$$

The autocorrelation function can be defined from PSD as:

$$r_{xx}(\tau)=\frac{1}{2\pi}\int_{-\infty}^{\infty} S_{xx}(\omega)e^{j\omega\tau}d\omega \tag{3}$$

The PSD is related to the autocorrelation function by the Wiener-Khintchine theorem. In fact, this theory states that the physically meaningful power spectral density can be calculated by:

$$S_{xx}(\omega)=\lim_{T\to\infty}\frac{1}{T}E\left\{\left|X_T(\omega)\right|^2\right\} \tag{4}$$

in which

$$X_T(\omega)=x(t)\times rect(\frac{t}{T}) \tag{5}$$

$$rect(t)=\begin{cases}1 & for|t|\le 0.5\\ 0 & otherwise\end{cases} \tag{6}$$

## 2. Least square distance

One of the well-known methods for pattern recognition and damage detection is the matching method (Qiao *et al.* 2012). Generally, the matching method is used for determining the similarity between two Curves, shapes, etc. The matching method is widely used in speech identification and fingerprint recognition. With the match between the new patterns with stored patterns in the database, the matching method detects damage. Three known algorithms in the matching method are a) Correlation algorithm, b) Least Square Distance algorithm and c) Cosh spectral distance algorithm. Regarding the capability of Least Square Distance (LSD) algorithm, this method has been used for this research. LSD algorithm has been widely used for speaker identification and fingerprint recognition. The results obtained from the PSD are as follows:

$$PSD_i^h = \begin{bmatrix} S_{i1}^h & S_{i2}^h & \dots & S_{in}^h \end{bmatrix} \tag{7}$$

$$PSD_i^d = \begin{bmatrix} S_{i1}^d & S_{i2}^d & \dots & S_{in}^d \end{bmatrix} \tag{8}$$

where, S represents the value of PSD matrix and n is the number of values. h and d indicate healthy and damaged structure, respectively. i is the pier number.

$$\Delta_i = \left[ \sqrt{\left(S_{i1}^h - S_{i1}^d\right)^2} \quad \sqrt{\left(S_{i2}^h - S_{i2}^d\right)^2} \quad \dots \quad \sqrt{\left(S_{in}^h - S_{in}^d\right)^2} \right] \tag{9}$$

$$D_i = \sum_{k=1}^{n} \Delta_{ik} \tag{10}$$

$$D-Index_i = \frac{D_i}{\max D_i (i=1 \quad to \quad m)} \times 100 \tag{11}$$

Herein, k is equal to the number of piers. For each of piers, the D-Index is calculated. The lower value of the index reflects the similarity between the PSDs of the healthy and damaged structure, and vice versa. The calculated indices are normalized to the largest value.

## 3. Proposed algorithm to damage detection

After the damage event, the structure and consequently the bridge can not behave like it was originally designed. In fact, after the damage occurs, the stiffness of the bridge is usually decreased and its damping is increased. The structural elements of the bridge due to damage probably experience some variations in dynamic properties and modal parameters. Depending on the severity of the damage, changes in the dynamic properties are different. Using the eigenvalue equations, the healthy and damaged structure can be described as follows:

$$[K]^h \{\phi_n\}^h = \lambda_n^h [M] \{\phi_n\}^h \tag{12}$$

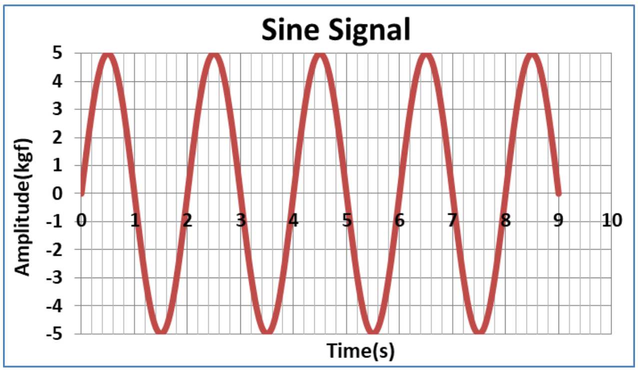


Figure 1 Sine exciting force

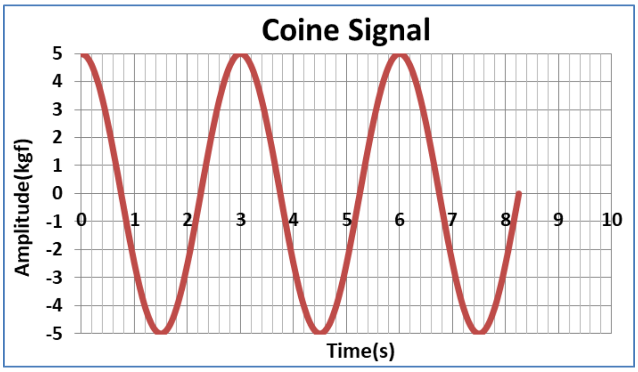


Figure 2 Cosine exciting force

$$[K]^d \{\phi_n\}^d = \lambda_n^d [M] \{\phi_n\}^d \tag{13}$$

in which, $[K]^d$ and $[K]^h$ are the healthy global stiffness matrix and the damaged global stiffness matrix of the structure. [M] is the mass matrix of the structure. $\lambda_n$ and $\{\phi_n\}$ are the n[th] eigenvalue and eigenvector of the structure which they are distinguished by h and d superscript for the healthy and damaged structure, respectively. Changes in the stiffness of the structure caused by damage can be defined as below:

$$[K]^d = [K]^h - [\Delta K] \tag{14}$$

$[\Delta K]$ is the change matrix, represents changes in the stiffness matrix due to the damages. By using equations 12 and 13, the following equation is obtained:

$$[\Delta K] = \left(\lambda^h - \lambda^d\right)[M] \tag{15}$$

In fact, the changes in the stiffness matrix are directly related to changes in the dynamic characteristics of the structure. Using the PSD and processing of responses, the dynamic properties of the structure can be extracted. Nevertheless, by evaluating and comparing the calculated characteristics, damages in the structure can be detected.

The main hypothesis of this study is based on the fact that the damage in the pier of the bridge causes disruption in the dynamic responses near its location. Nevertheless, the dynamic responses resulting from the vibration of the bridge's piers in the damaged state changes in comparison to the healthy state. These differences between the dynamic responses of the pier, usually cannot be distinguished from

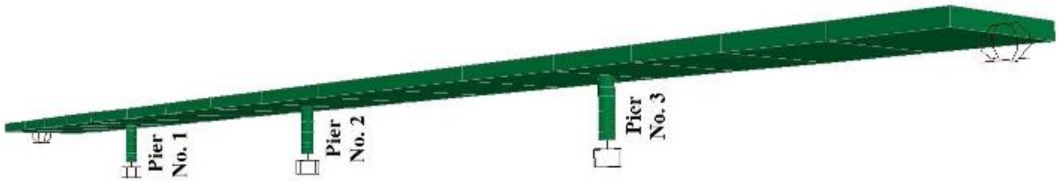


Figure 3 View from the analytical model of W180 bridge

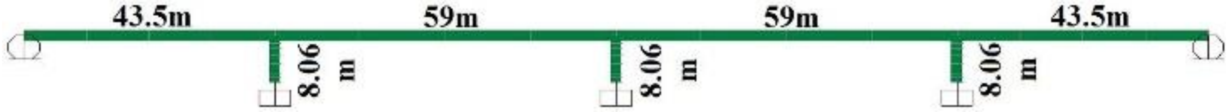


Figure 4 Dimension of the analytical model of W180 bridge

the recorded signals. But if the signals are processed by the PSD, these changes are likely to be determined.

In this research, a new algorithm is proposed to identify damage in concrete piers of bridges. The proposed algorithm is easy, usable and applicable to identify damage in bridge piers. Based on the algorithm, an accelerometer sensor should be installed at the midpoint of each pier height of the bridge. After installing the sensors, an exciting load is applied to the bridge and its responses at the piers are recorded. After the damage event, the exciting load is applied again to the bridge and its responses are registered. The recorded signals are processed by PSD and the modal amplitude for each frequency is calculated. The processing results are evaluated using the least squares method. In the proposed algorithm, it is not necessary to measure the input power that is the algorithm's characteristic. In addition, this algorithm, unlike many other methods, does not need 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 loads. The first is a sine function of angular frequency equal to (Figure 1), and the second is a cosine function of angular frequency equal to (Figure 2).

Using PSD function, the recorded responses were processed and dynamic characteristics were extracted. The pattern recognitions on the computed information were done using the least squared distance method.

## 4. Evaluate the proposed algorithm

To evaluate the proposed algorithm, the analytical model of W180 bridge was selected as the structural sample. In the following subsections, the bridge model is first introduced. Based on the algorithm, the bridge responses under exciting loads are registered and their features are extracted by PSD function. Moreover, for pattern recognition and damage detection, LSD method is used.

### *4.a Analytical Model of W180 Bridge*

W180 is a concrete bridge of 205 meters in length. The width and height of the bridge deck are 16.37 meters and 1.75 meters, respectively. W180 bridge has 4 spans and 3 piers. The cross-section of piers is circular with a diameter of 1.8 meters. The analytical model of W180 bridge was first used by researchers at the University of California, Berkeley, and the University of Central Florida (Aviram *et al.* 2008). A view from the bridge model and dimensions of the model are shown in Figure 3 and Figure 4, respectively.The first period of the bridge is 1.55s and the second period is 1.04s.

Table 1 Damage scenarios in the piers

| row | damaged element | severity of damage |
|---|---|---|
| scenario1 | Pier 2-ele#1 | 50% |
| scenario2 | Pier 2-ele#4 | 30% |
| scenario3 | Pier 2-ele#9 | 10% |
| scenario4 | Pier 1&3-ele#5 | 30% |
| scenario5 | Pier 1&3-ele#8 | 15% |

The stress-strain relation for concrete is defined by Mander model. Furthermore, piers and deck are modeled by the frame element. The bridge model has 36 nodes and 45 frame elements. The model was analyzed with regard to the gravity loads.

To validate the applicability of the proposed algorithm, three different damage scenarios were considered in thebridge model. Each of the piers is divided into 9 elements at a height. The damages considered in different scenarios are presented in Table 1. In order to inflict damages on the analytical model, the stiffnesses of the considered elements were reduced.

### *4.b Feature extraction*

As already mentioned, in this study a new algorithm is suggested to 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 and before and after happening the damage, its responses at the piers are registered. The responses were processed by Power Spectral Density function. The diagrams of Power Spectral Density related to the response signals of the pier No. 2 are shown in figures 5 and 6.

### *4.c Damage detection*

Now using the results of PSD, the performance of the method and damage index is evaluated. The results of using the proposed method are shown in Figures 7 to 11. Based on Scenario 1, pier 2 has been damaged. As shown in Fig. 7, the damaged pier is appropriately identified by the proposed

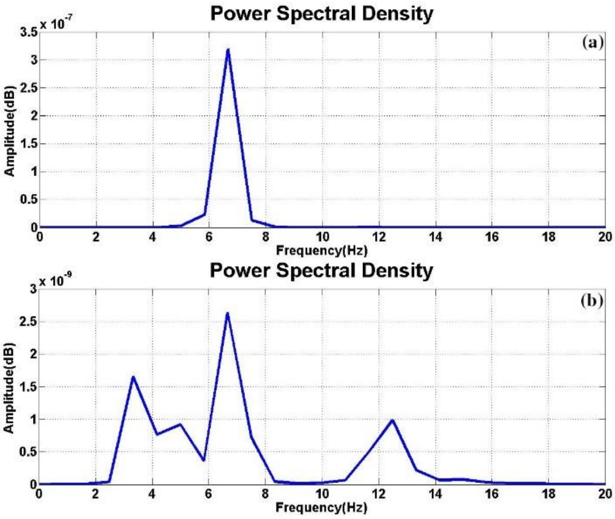


Figure 5 Diagrams of Power Spectral Density Function Based on the Recorded Responses of the Healthy Pier2, Affected by a) Sine Exciting Force and b) Cosine Exciting Force

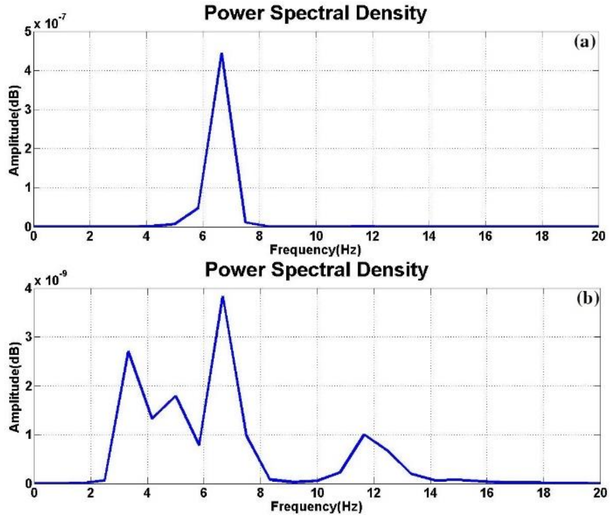


Figure 6 Diagrams of Power Spectral Density Function Based on the Recorded Responses of the Damaged Pier2in scenario1, Affected by a) Sine Exciting Force and b) Cosine Exciting Force

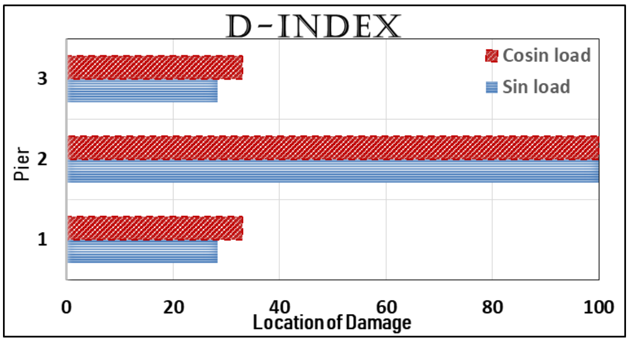


Figure 7 Diagnosis the damaged pier in scenario 1 using the D-Index

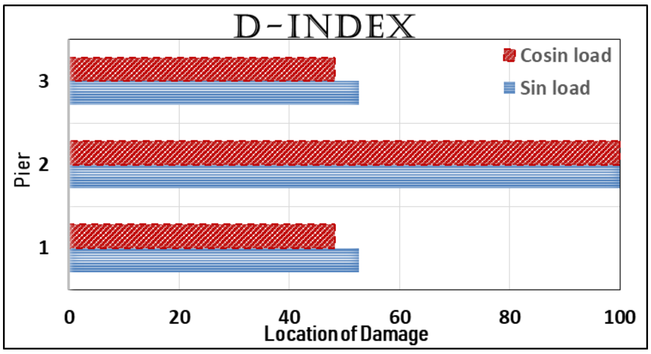


Figure 8 Diagnosis the damaged pier in scenario 2 using the D-Index

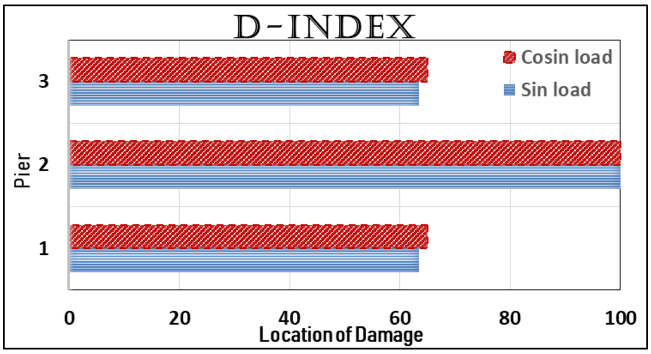


Figure 9 Diagnosis the damaged pier in scenario 3 using the D-Index

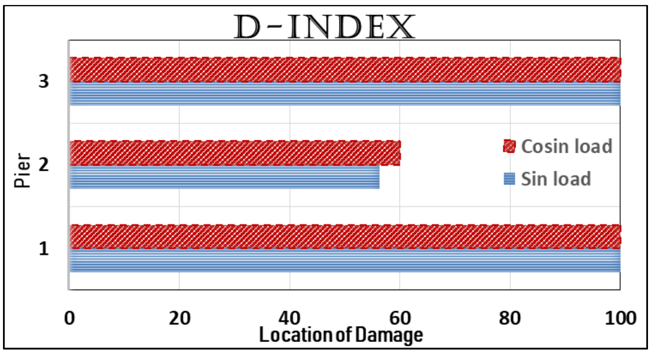


Figure 10 Diagnosis the damaged pier in scenario 4 using the D-Index

index. Based on the results presented in Fig. 8, the value of the index at pier 2 is equal to 100. While in piers 1 and 3, it is calculated equal to 60 and 70, respectively. However, the D-Index correctly diagnosed the damaged pier in Scenario 2. According to Fig. 9, the performance of the proposed method in Scenario 3 is also good and the damaged pier is identified. The error rate has increased with decreasing severity of damage. This is because by reducing the severity of damage, the similarity of the recorded signals in both healthy and damaged conditions increases. As shown in Table 1, in scenarios 4 and 5, the damage is considered simultaneously in two piers. In accordance with Fig. 10, the calculated value of D-Index in piers 1, 2, and 3 is 100, 60 and 100, respectively. Therefore, despite the damage event in two different columns, the suggested index correctly identified the damaged columns. The D-Index correctly detects damaged piers in scenario 5. The results of the calculations for scenario 5 are shown in Fig. 11. According

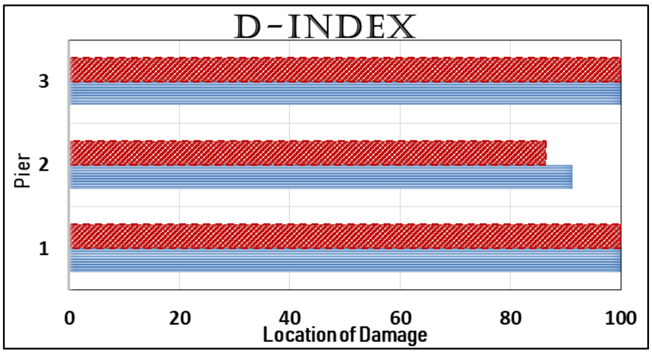

Figure 11 Diagnosis the damaged pier in scenario 5 using the D-Index

to the results, the proposed method and Index, despite its simplicity and applicability, correctly identified the damage and determined its location.

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

## 5. Conclusion

In this study, a new algorithm based on power spectral density function and Least Square Distance method, was proposed to detect damage in concrete piers of bridges. The new algorithm is presented in a way that is as simple and practical as possible and also demonstrates it performs well.In this algorithm, the vibrations of the columns are recorded only through an accelerometer sensor. Besides, the algorithm does not need the numerical model for system identification and damage detection. In addition, the proposed approach does not need to measure the input force. In other words, the algorithm can extract the dynamic properties of the bridge and detect possible damage_ only through recorded responses from bridge piers.

To evaluate the proposed algorithm, the analytical model of W180 bridge, was selected as the structural sample. In addition, 5 different damage scenarios were considered. The damage is assumed in different piers with different intensities. Based on the calculated results, the proposed algorithm and index correctly detects damages in all scenarios. Therefore, considering the simplicity and applicability of the proposed algorithm and D-Index, they can be used in health monitoring of bridges.

## References


Ahmadi, H.R. and Anvari, D. (2018), "New damage index based on least squares distance for damage diagnosis in steel girder of bridge's deck", *Struct. Control Health Monitoring*, **25**(10). https://doi.org/10.1002/stc.2232.

Ahmadi, H.R., Daneshjoo, F. and Khaji, N. (2015), "New damage indices and algorithm based on square time-frequency distribution for damage detection in concrete piers of railroad bridges", *Struct. Control Health Monitoring*, **22**, 91-106. https://doi.org/10.1002/stc.1662.

Aviram, A., Mackie, K.R. and Stojadinović, B. (2008), "Guidelines for nonlinear analysis of bridge structures in California", Pacific Earthquake Engineering Research Center, California, USA.

Bayat, M., Daneshjoo, F. and Nistico, N. (2015), "A novel proficient and sufficient intensity measure for probabilistic analysis of skewed highway bridges", *Struct. Eng. Mech.*, **55**(6), 1177-1202. https://doi.org/10.12989/sem.2015.55.6.1177.

Bernal, D. (2002), "Load vectors for damage localization", *J. Eng. Mech.*, **128**, 7-14. https://doi.org/10.1061/(ASCE)0733-9399(2002)128:1(7).

Cornwell, P., Doebling, S.W. and Farrar, C.R. (1999), "Application of the strain energy damage detection method to plate-like structures", *J. Sound Vib.*, **224**(2), 359-374. https://doi.org/10.1006/jsvi.1999.2163.

Doebling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D.W. (1996), "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review", LA-13070-MS; Los Alamos National Lab., NM, USA.

Du, A., Padgett, J.E. and Shafieezadeh, A. (2019), "A posteriori optimal intensity measures for probabilistic seismic demand modelling", *Bullet. Earthq. Eng.*, **17**(2), 681-706. https://doi.org/10.1007/s10518-018-0484-8.

Duran, B., Tunaboyu, O., Kaplan, O. and Avsar, O. (2018), "Effectiveness of seismic repairing stages with CFRPs on the seismic performance of damaged RC frames", *Struct. Eng. Mech.*, **67**(3), 233-244. http://doi.org/10.12989/sem.2018.67.3.233.

Fang, S.E. and Perera, R. (2009), "Power mode shapes for early damage detection in linear structures", *J. Sound Vib.*, **324(**1-2**)**: 40-56. https://doi.org/10.1016/j.jsv.2009.02.002.

Fereshtehnejad, E., Hur, J., Shafieezadeh, A., Brokaw, M., Backs, J., Noll, B. and Waheed, A. (2018), "A bridge performance index with objective incorporation of safety risks", *Proceedings of Transportation Research Board 97th Annual Meeting*, Washington DC, USA, January.

Gallego, A., Benavent-Climent, A. and Romo-Melo, L. (2015), "Piezoelectric sensing and non-parametric statistical signal processing for health monitoring of hysteretic dampers used in seismic-resistant structures", *Mech. Syst. Signal Process.*, **60**, 90-105.

Havelock, D., Kuwano, S. and Vorländer, M. (2008), "Handbook of signal processing in acoustics", Springer Science and Business Media, Berlin, Germany.

Jorquera Lucerga, J.J., Lozano Galant, J.A. and Turmo Coderque, J. (2016), "Structural behavior of non-symmetrical steel cable-stayed bridges", *Steel Compos. Struct.*, **20**(2), 447-468. http://dx.doi.org/10.12989/SCS.2016.20.2.447.

Kia, M. and Banazadeh, M. (2016), "Closed-form fragility analysis of the steel moment resisting frames", *Steel Compos. Struct.*, **21**(1), 93-107.

Kia, M. and Banazadeh, M. (2017), "Probabilistic seismic hazard analysis using reliability methods", *Scientia Iranica*, **24**(3), 933-941.

Kim, J.T., Ryu, Y.S., Cho, H.M. and Stubbs, N. (2003), "Damage identification in beam-type structures: frequency-based method vs mode-shape-based method", *Eng. Struct.*, **25**(1) 57-67.

Kutanaei, S.S. and Choobbasti, A.J. (2015), "Mesh-free modeling of liquefaction around a pipeline under the influence of trench layer", *Acta Geotechnica*, **10**(3), 343-355.

Kutanaei, S.S. and Choobbasti, A.J. (2016), "Experimental study of combined effects of fibers and nanosilica on mechanical properties of cemented sand", *J. Mater. Civil Eng.*, **28**(6), https://doi.org/10.1061/(ASCE)MT.1943-5533.0001521.

Kutanaei, S.S. and Choobbasti, A.J. (2019), "Prediction of liquefaction potential of sandy soil around a submarine pipeline under earthquake loading", *J. Pipeline Syst. Eng. Practice*, **10**(2), https://doi.org/10.1061/(ASCE)PS.1949-1204.0000349.

Lee, Eun-Taik and Hee-Chang Eun (2016), "Structural damage detection by power spectral density estimation using output-only measurement", *Shock Vib.*, **2016**, https://doi.org/10.1155/2016/8761249.

Li, H., Wang, J. and Hu, S.L.J. (2008), "Using incomplete modal data for damage detection in offshore jacket structures", *Ocean Eng.*, **35**(17-18), 1793-1799. https://doi.org/10.1016/j.oceaneng.2008.08.020.

Liu, F., Li, H., Li, W. and Wang, B. (2014), "Experimental study of improved modal strain energy method for damage localisation in jacket-type offshore wind turbines", *Renewable Energy*, **72**, 174-181. https://doi.org/10.1016/j.renene.2014.07.007.

Liu, L., Su, H. and Lei, Y. (2017), "Probabilistic damage detection of structures with uncertainties under unknown excitations based on Parametric Kalman filter with unknown Input", *Struct. Eng. Mech.*, **63**(6), 779-788. http://dx.doi.org/10.12989/sem.2017.63.6.779.

Masciotta, M.G., Ramos, L.F., Lourenço, P.B., Vasta, M. and De Roeck, G. (2016), "A spectrum-driven damage identification technique: Application and validation through the numerical simulation of the Z24 Bridge", *Mech. Syst. Signal Process.*, **70**, 578-600. https://doi.org/10.1016/j.ymssp.2015.08.027.

Meymian, N.Z., Clark, N.N., Musho, T., Darzi, M., Johnson, D. and Famouri, P. (2018), "An optimization method for flexural bearing design for high-stroke high-frequency applications". *Cryogenics*, **95**, 82-94. https://doi.org/10.1016/j.cryogenics.2018.09.008.

Nabizadeh, A., Tabatabai, H. and Tabatabai, M.A. (2018), "Survival analysis of bridge superstructures in Wisconsin", *Appl. Sci*., **8**, 2079. https://doi.org/10.3390/app8112079.

Nabizadehdarabi, A. (2015), "Reliability of bridge superstructures in Wisconsin", M.Sc. Dissertation, University of Wisconsin Milwaukee, USA.

Najafabadi, A.A., Daneshjoo, F. and Bayat, M., (2017), "A novel index for damage detection of deck and dynamic behavior of horizontally curved bridges under moving load", *J. Vibroeng.*, **19**(7), 5421-5433. https://doi.org/10.21595/jve.2017.19370.

Pau, A., Greco, A. and Vestroni, F. (2011), "Numerical and experimental detection of concentrated damage in a parabolic arch by measured frequency variations", *J. Vib. Control*, **17**(4), 605-614. https://doi.org/10.1177/1077546310362861.

Pradhan, S. and Modak, S.V. (2012), "Normal response function method for mass and stiffness matrix updating using complex FRFs", *Mech. Syst. Signal Process.*, **32**, 232-250. https://doi.org/10.1016/j.ymssp.2012.04.019.

Qiao, L. (2009), "Structural damage detection using signal-based pattern recognition", Ph.D. Dissertation, Kansas State University, USA.

Qiao, L., Esmaeily, A. and Melhem, H.G. (2012), "Signal pattern recognition for damage diagnosis in structures", *Comput. Aid Civil Infrastruct. Eng.*, **27**(9), 699-710. https://doi.org/10.1111/j.1467-8667.2012.00766.x.

Rahmatalla, S., Eun, H.C. and Lee, E.T. (2012), "Damage detection from the variation of parameter matrices estimated by incomplete FRF data", *Smart Struct. Syst.*, **9**(1), 55-70. http://dx.doi.org/10.12989/sss.2012.9.1.055.

Sakka, Z.I., Assakkaf, I.A. and Qazweeni, J.S. (2018), "Reliability-based assessment of damaged concrete buildings", *Struct. Eng. Mech.*, **65**(6), 751-760. http://dx.doi.org/10.12989/sem.2018.65.6.751.

Sazonov, E. and Klinkhachorn, P. (2005), "Optimal spatial sampling interval for damage detection by curvature or strain energy mode shapes", *J. Sound Vib.*, **285**(4-5), 783-801. https://doi.org/10.1016/j.jsv.2004.08.021.

Shao, C., J.W. Ju, Han, G. and Qian, Y. (2017), "Seismic applicability of a long-span railway concrete upper-deck arch bridge with CFST rigid skeleton rib", *Struct. Eng. Mech.,* **61**(5), 645-655. http://dx.doi.org/10.12989/sem.2017.61.5.645.

Sohn, H., Farrar, C.R., Hemez, F.M., Shunk, D.D., Stinemates, D. W., Nadler, B.R. and Czarnecki, J.J. (2003), "A review of structural health monitoring literature: 1996-2001", LA-UR-02-2095; Los Alamos National Laboratory, USA.

Stoica, P. and Moses, R.L. (2005), *Spectral Analysis of Signals*, Prentice Hall, Inc., New Jersey, USA.

Tabatabai, H., Sobolev, K., Ghorbanpoor, A., Nabizadeh, A., Lee, C. and Lind, M. (2016), *Evaluation of Thin Polymer Overlays for Bridge Decks*. Wisconsin Highway Research Program, Madison, USA.

Tang, J.P., Chiou, D.J., Chen, C.W., Chiang, W.L., Hsu, W.K., Chen, C.Y. and Liu, T.Y. (2011), "RETRACTED: A case study of damage detection in benchmark buildings using a Hilbert-Huang Transform-based method", *J. Vib. Control*, **17**(4), 623-636. https://doi.org/10.1177/1077546309360053.

Wahab, M.A. (2001), "Effect of modal curvatures on damage detection using model updating", *Mech. Syst. Signal Process.*, **15**(2), 439-445. https://doi.org/10.1006/mssp.2000.1340.

Walia, S.K., Vinayak, H.K., Kumar, A. and Parti, R. (2015), "Modal parametric changes in a steel bridge with retrofitting", *Steel Compos. Struct.,* **19**(2), 385-403. http://dx.doi.org/10.12989/scs.2015.19.2.385.

Yan, W.J. and Ren, W.X. (2012), "Operational modal parameter identification from power spectrum density transmissibility", *Comput. Aid Civil Infrastruct. Eng.*, **27**(3), 202-217. https://doi.org/10.1111/j.1467-8667.2011.00735.x.

Yan, W.J., Ren, W.X. and Huang, T.L. (2012), "Statistic structural damage detection based on the closed-form of element modal strain energy sensitivity", *Mech. Syst. Signal Process.*, **28**, 183-194. https://doi.org/10.1016/j.ymssp.2011.04.011.

Yan, Y.J., Cheng, L., Wu, Z.Y. and Yam, L.H. (2007), "Development in vibration-based structural damage detection technique", *Mech. Syst. Signal Process.*, **21**(5), 2198-2211.

Yang, Y.B. and Yang, J.P. (2018), "State-of-the-art review on modal identification and damage detection of bridges by moving test vehicles", *J. Struct. Stability Dynam.*, **18**(02), https://doi.org/10.1142/S0219455418500256.

Yin, X., Liu, Y. and Kong, B. (2016), "Vibration behaviors of a damaged bridge under moving vehicular loads", *Struct. Eng. Mech.*, **58**(2), 199-216. http://dx.doi.org/10.12989/sem.2016.58.2.199.

Zhang, D. and Johnson, E.A. (2012), "Substructure identification for shear structures: cross-power spectral density method", *Smart Mater. Struct.*, **21**(5), https://doi.org/10.1088/0964-1726/21/5/055006.

Zhang, D. and Johnson, E.A. (2014), "Substructure identification for plane frame building structures", *Eng. Struct.*, **60**, 276-286. https://doi.org/10.1016/j.engstruct.2013.12.008.

Zheng, Z.D., Lu, Z.R., Chen, W.H. and Liu, J.K. (2015), "Structural damage identification based on power spectral density sensitivity analysis of dynamic responses", *Comput. Struct.*, **146**, 176-184. https://doi.org/10.1016/j.compstruc.2014.10.011.

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