Journal of Engineering Science and Technology
Vol. 12, No. 12 (2017) 3274 - 3285

DAMAGE IDENTIFICATION IN A MULTILEVEL STRUCTURE USING EMPIRICAL MODE DECOMPOSITION

D. MALLIKARJUNA REDDY[1,*], I. R. PRAVEEN KRISHNA[2]

[1]School of Mechanical Engineering, VIT University, Vellore, 632014, India
[2]Indian Institute of Space Science and Technology, Kerala, 695547, India
[*]Corresponding Author: dmreddy@vit.ac.in

Abstract

The use of the method of Empirical Mode Decomposition (EMD) is explored for the detection of changes in the structural response data of multi-level structure investigated experimentally. A three level structure is excited using a band limited white noise covering initial ten natural frequencies. Damage to the structure is simulated by giving impulse on a level. Firstly adopt EMD technique to decompose the response signal of structure vibration into several mono-component signals called Intrinsic Mode Functions (IMF), which is used to indicate the presence of location with spike of a damaging event in a structure monitored continuously. Also investigated the effectiveness of the EMD method with noisy data signals are added some percentage of noise to the excitation source and proved that EMD technique is able to detect the damage instant in the structure. From the analysis proved that the EMD method is capable of identifying damage presence and location, if the structure is monitored on a continuous basis and the damage occurs suddenly.

Keywords: Damage detection, intrinsic mode function, Condition monitoring, Empirical mode decomposition.

1. Introduction

Vibration-based structural damage detection methods have attracted considerable attention in recent years for the assessment of health and safety of large civil structures. An overview of methods to detect, locates, and characterizes damage in structural and mechanical systems by examining changes in measured vibration response. Research in vibration-based damage identification has been rapidly expanding over the last few years. The basic idea behind this technology is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness) [1]. Therefore, changes in the physical properties will cause detectable changes in the modal

Abbreviations	
EMD	Empirical Mode Decomposition
IMF	Intrinsic Mode Functions
PZT	Piezo devices made of lead Zirconate Titanate

properties. Although modal parameter response methods have demonstrated various degrees of success in damage detection of small structures, there are several confounding factors making these methods difficult to implement in large civil structures. One issue of primary importance is that modal parameter response methods presume access to a date set from the undamaged structure, which is often not available for most existing civil structures. Another factor is that most of modal parameter response methods operate with data recorded before and after the occurrence of structural damage: The structural behaviour during the data collection is assumed linear. The identified modal parameters and the properties derived from the modal parameters (the damage indices) are only the average characteristics over the data duration and may not be sensitive enough to structural damage that typically is a local phenomenon. Consequently, if for any reason there is a sudden damage event occurring during the measurement period, these methods cannot be used to find when the damage event occurs.

In contrast to a large number of publications pertaining to damage indices using the average modal characteristics, there is a paucity of researches addressing instantaneous damage indices. To acquire a damage feature retaining damage time instant, the application of time-frequency data processing tool for analyzing the raw measurement data is necessary. The logical candidates include the wavelet analysis and the newly emerged signal processing technique, that is, the empirical mode decomposition Huang et al. [2, 3]. Zhu and Law [4] first suggested that by performing a continuous wavelet transform (CWT) on the deflection-time signal of a cracked beam subject to a constant moving load, it was possible to determine the position of the crack. Reddy and Swarnamani [5] the strain energy data is used for wavelet transform and show the effectiveness of the wavelet transform in the damage detection in plate structure.

Sun and Chang [6] proposed a wavelet packet transform-based method for the damage assessment. Dynamic signals measured from a structure were first decomposed into wavelet packet components in the time domain. Component energies were then calculated and used as inputs into neural network models for damage assessment. Hou et al. [7, 8] proposed a wavelet-based approach to identify the damage time instant and damage location of a simple structural model with breakage springs. The suddenly breakage of structural element will cause discontinuity in the response signal measured in the vicinity of the damage location. By decomposing the response signal in the time domain using the wavelet analysis, the discontinuity will form a signal feature, termed damage spike, in the wavelet details. The damage time instant can then be identified in terms of the occurrence time of spike, and the damage location can be determined by the spatial distribution of the observed spikes.

Chen et al. [9] the signal discontinuity of the structural acceleration responses of an example building is extracted based on the discrete wavelet transform. It is proved that the variation of the first level detail coefficients of the wavelet transform at damage instant is linearly proportional to the magnitude of the stiffness reduction. Yang et al. [10], Pines and Salvino [11] and Yinfeng et al. [12] He et al. [13] also demonstrated the ability of EMD to detect structural damage; however, it had not been tested for structures subject to moving loads until Bradley et al. [14]. This investigation concluded that EMD could be used to detect damage from the accelerations of a beam model subject to the crossing of a load. They applied a high-pass filter to the IMFs, resulting from the acceleration response, to detect a single damaged location. It was found that high levels of noise and long beam lengths introduced some small inaccuracies; however, these could be reduced with an increase in observation points. Vincent et al. [15] and Yang et al. [16] Garcia-Perez et al. [17] investigated to identify the damage time instant by using Empirical mode decomposition to decompose the response signal to capture the signal discontinuity. Numerical simulations carried out and showed that the EMD approach is promising method to identify the damage time instant and damage location using the signal feature of damage spike. Xu and Chen [18] conducted experiments on the use of EMD using a three storey steel frame building model.

A sudden change of structural stiffness was simulated and signals were acquired using accelerometers. The measured structural response time history from each test case was processed using the EMD approach with intermittency check. The first IMF components were then used to identify the damage time instant and damage location in the building [19]. Yu et al. [20] proposed a generic optimal methodology to improve the accuracy of positioning of the flaw in a structure. This novel approach involves a two-step process. The first step essentially aims at extracting the damage-sensitive features from the received signal, and these extracted features are often termed the damage index or damage indices, serving as an indicator to know whether the damage is present or not. In particular, a multilevel SVM (support vector machine) plays a vital role in the distinction of faulty and healthy structures. Formerly, when a structure is unveiled as a damaged structure, in the subsequent step, the position of the damage is identified using Hilbert-Huang transform. Also compared with the wavelet-based approach for which a proper mother wavelet as well as a decomposition level should be decided before decomposition, the EMD approach processes more attractive application potentials because it decomposes the signal based on the time scale of the signal itself with adaptive nature.

Nevertheless, the aforementioned studies using either the wavelet analysis or the EMD approach are based on numerical simulations. Several important assumptions involved in the numerical studies have not been verified yet. Extensive experimental investigations and verifications of the EMD approach are thus desirable and necessary before it can be applied to real civil structures.

Despite of the extensive literature studies of vibration analysis on damaged structures, only few effective and practical techniques are found for very small damage identification. In this connection, this paper presents an experimental investigation on the applicability of EMD method for identifying structural damage caused by a sudden change of structural stiffness. Therefore, focused on the study of empirical mode decomposition is explored for the detection of changes in the structural response of multi-level structure investigated experimentally. Also each response signals is analyzed with EMD method to detect to identify location and severity of damage event.

2. Introduction of Empirical Mode Decomposition method

The empirical mode decomposition, developed by Huang et al. [2] can decompose and data set into several intrinsic mode functions (IMFs), which admits well behaved Hilbert transform, by a procedure called sifting process. Suppose $y(t)$ is the signal to be decomposed. The sifting process is conducted by first constructing the upper and lower envelop of $y(t)$ by connecting its local maxima and local minima through a cubic spline. The mean of two envelopes is then computed and subtracted from the original time history. The difference between the original time history and the mean value is called the first IMF, c1, if it satisfies the following two conditions: (1) within the data range, the number of extrema and the number of zero-crossings are equal or differ by one only and (2) the envelope defined by the local maxima and the envelope defined by the local minima are symmetric with respect to the mean. The difference between $y(t)$ and c1 is then treated as a new time history and subjected to the same sifting process, giving the second IMF c2. The sifting procedure continues until the residue becomes so small that it is less than a predetermined value of consequence, or the residue becomes a monotonic function. The original time history $y(t)$ is finally expressed as the sum of the IMF components plus the final residue. Recent developments of EMD and sifting process can be found in Yu and Ren [20], Huang et al. [21], and Wu and Huang [22].

$$\boldsymbol{y(t) = c_1(t) + \sum_{j=2}^{N-1} c_j(t) + c_N + r_N(t)} \quad (1)$$

where:

$\boldsymbol{c_1(t)} =$ High frequency component used for damage detection.

$\boldsymbol{\sum_{j=2}^{N-1} c_j(t)}$ = Mid-frequency component used for parameter identification.

$\boldsymbol{c_N + r_N(t)}$ = Low frequency component used for data pre-processing.

It is seen that EMD is adaptive and decomposes the signal based on the local characteristics of the data itself. After EMD decomposition, the first IMF component, $c_1(t)$, has the highest frequency content of the original signal while the final residue, $r(t)$, represents the component of the lowest frequency in the signal. By acknowledging the physical meaning of different parts of the EMD decomposition results, to tackle different problems within SHM system.

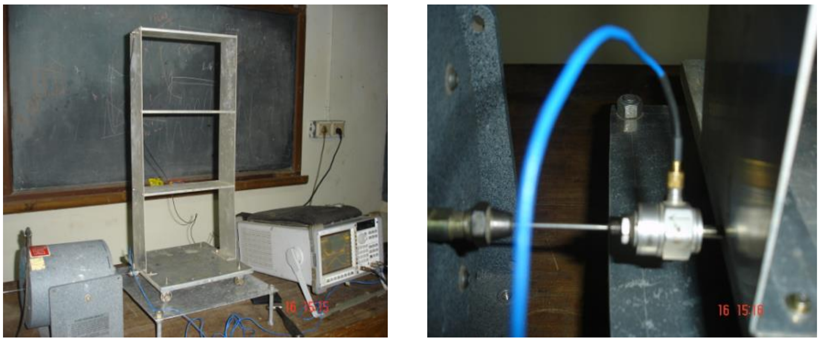
3. Experimental Set-up

The multilevel Aluminium structure with instrumentation set up as shown in Fig. 1(a), the levels are 30 and 10 cm in length and width respectively with thickness of 0.6 cm. All three levels connected to the walls at equal distances. Each level has a mass of 0.54 kg. The levels attached to the side walls using two screws on each side. The walls are 60 and 10 cm length and width respectively with thickness of 0.2 cm connects at the base. The mass of each wall is 0.26 kg. The structure is bolted through the base to a moving plate.

The plate is 30 cm^2 in area and 1.2 cm thick. Ball bearings mounted to the plate to allow it to move freely (in one direction) upon a fixed base that is securely mounted to the bench. Moving plate connected with the help of 10 cm long connecting rod of diameter 0.2 cm and then to MB electro dynamic shaker as shown in zoomed view Fig. 1(b). The shaker is relatively small, with diameter of 18.5 cm and a length of 21.5 cm.

The maximum displacement is 25 mm peak to peak, and it delivers 220 N of force. As per the manufacturer, the usable bandwidth of the shaker lies between 1 Hz to 4 kHz. Model 3145A LIVM accelerometers (Dytran make ICP based) are attached at each level and the base to translate the acceleration of the structure into voltage signals. Accelerometer has a mass 2.7 gm.

The sensitivity of the accelerometer is 100 mV/g. A signal condition amplifier type 2626 amplifies this signal which is processed further as discussed in the results section. For data acquisition purpose Dactran focus four channel data acquisition with RT PRO 5.5 as driver software is used. The natural frequencies of the experimental structure were obtained by exciting the first eight modes which lies between 0 to 200 Hz using as forced excitation as shown in Fig. 2, Damage detection tests were performed using the white noise excitation, which includes frequencies in the range of 0 to 200 Hz and its amplitude oscillates between 4vpk. This excitation represents a general case of structural loads due to wing, ground motion, etc.



(a) **(b)**

Fig. 1. (a) Multilevel (three-level) structure for experiments, (b) Zoomed view of electro-dynamic shaker connected to base.

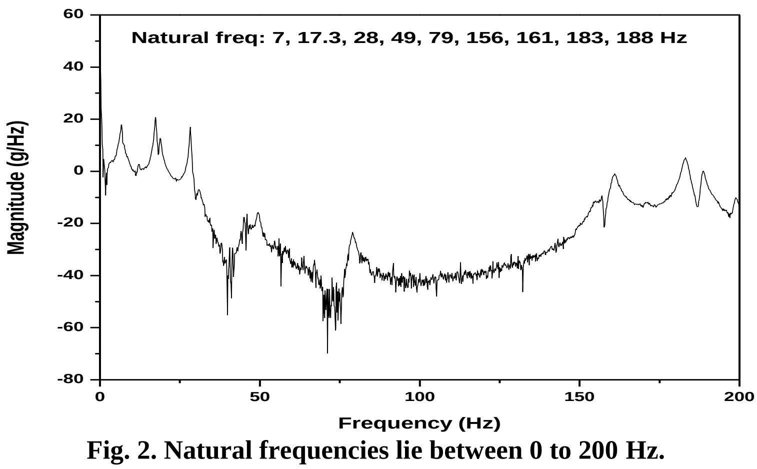


Fig. 2. Natural frequencies lie between 0 to 200 Hz.

4. **Results and discussions**

4.1. Sudden damage detection using EMD method

In the first case, the modification of impulse applied on level 3 (top) at approximately 3 seconds and the response of the structure is recorded. It is observed that the time history of the responses (Fig. 3) does not indicate any changes (damages) to the structure. This data analyzed using empirical mode decomposition (EMD) process, which yields the IMFs of the signal as shown in Fig. 3.

The initial IMF's has the highest frequency content of the signal. Therefore, damage detection is performed using to time history of IMF1and IMF2. Since the white noise excitation contains frequencies up to 200 Hz, structural responses at those frequencies are present in the data which make the determination of damage difficult. Hence an intermittency frequency is imposed during the EMD process which essentially removes data at lower frequencies. The process is similar to the method used by Yang et al. [10] and Xu and Chen [18].

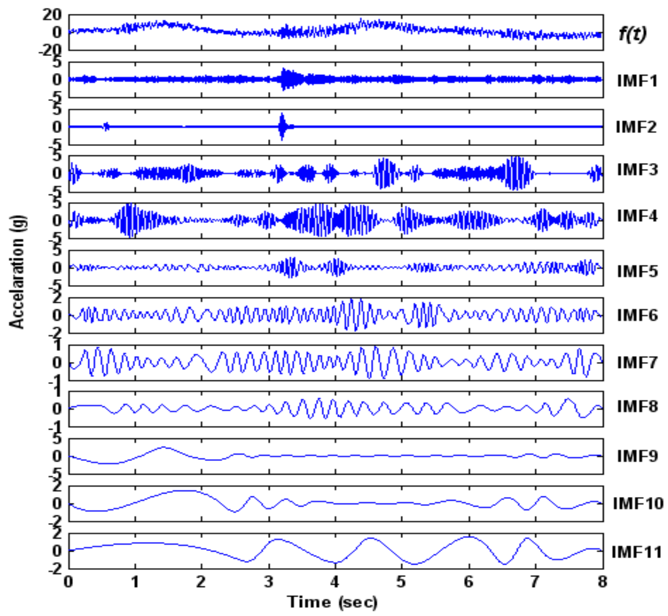
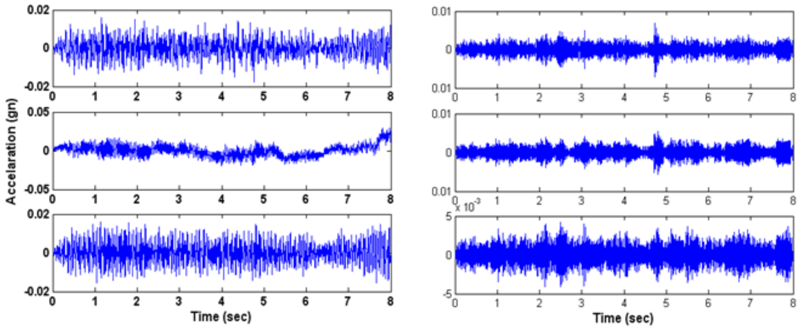


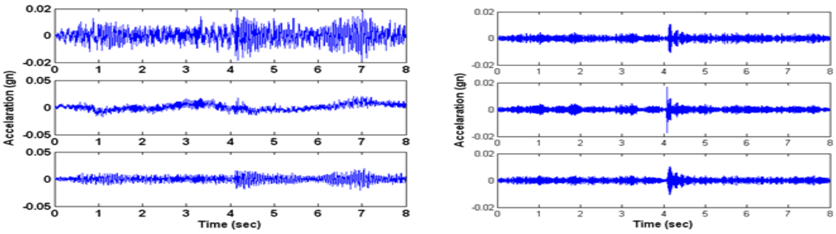
Fig. 3. The response signal and its intrinsic mode functions.

For case1 the modification of mass (50gm) placed on level 3 at approximately 4.7 s. The resulting response and IMF1 for all three levels are acquired and are shown in Figs. 4(a) and (b), respectively. The large spike at 4.7s in the level3 as observed from Fig. 4(b) clearly indicates damage caused to the structure at that time. The spike in level2 data is relatively small and level3 data has no visible spike. This indicates damage close to level3. Similarly, Fig. 5 shows the IMF1 for the modification of mass (50gm) placed on level2 at approximately 4s. The largest spike in IMF1for level2 again indicates damage with large spike close to level2. For the modification of mass placed on bottom level (level1) at approximately 4.3 s. The resulting responses and IMF signals are as shown in Fig. 5(b).



4(a) **4(b)**

Fig. 4. (a) Acceleration time history responses for level3 (top), level2 (middle), level1 (bottom) respectively (b) IMF1 for level3 (top), level2 (middle), level1 (bottom) for band limited white noise input (modification mass (50gm) placed on level 3 at approximately 4.7 s).



5(a) **5(b)**

Fig. 5. (a) Acceleration time history responses for level3 (top), level2 (middle), level1 (bottom) respectively (b) IMF1 for level3 (top), level2 (middle), level1 (bottom) for band limited white noise input (modification mass 50gm) placed on level 2 at approximately 4 s).

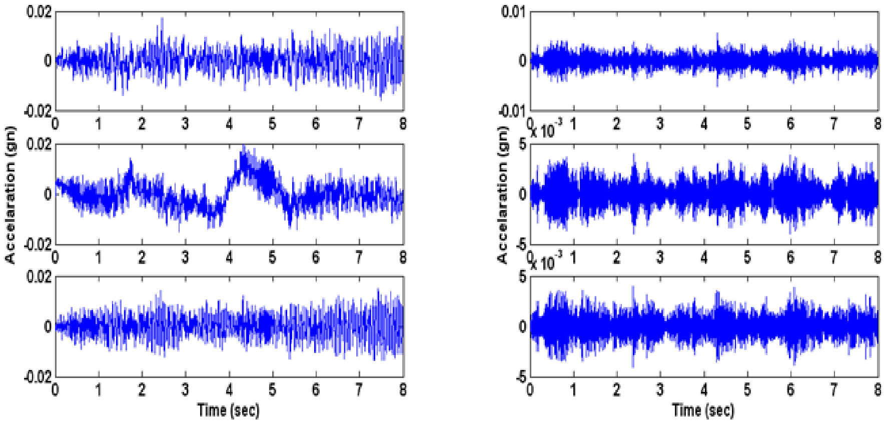
By observing Fig. 6(b), there is a spike at 4.3 s but not that much highlighted because response signal contain lot of noise. Similar analysis is carried out by placing the mass (100 gms) at middle level (level2) and respective IMFs are analyzed. Figure 7 shows largest spike approximately at 4 s which gives information about the severe damage close to level2.

In order to investigate the sensitivity of empirical mode decomposition (EMD) when there are chances of multiple damages occur in the structure. The same analysis is performed for a building structure containing damage at two locations. In this case the modification of mass (50gm) placed on level2 at approximately 3 and 6 seconds.

Figures 8(a) and (b) show the acceleration response signals and IMFs respectively. By observing the acceleration response signals in Fig. 8(a), it is very difficult to locate multiple damage. So after processing responses through the EMD respective IMFs of each level shows two spikes at approximately 3.2 and 6.2 s. The spike in level2 is relatively higher comparing to other levels.

Figure 9(a) shows the voltage applied to the PZT actuator (bonded at the left wall) increasing from 0V to 25 V at 4.8 s. The results for this second method of introducing damage to the structure are presented in Fig. 9(b), Similar to earlier results, the response time history does not indicate any event, but the IMF1 for level1 shows clear spikes and thereby identifies damage, occurring at 4.8 s.

The slight difference in the occurrence of spikes and PZT voltage changes is due to system time delay. Since there are no spikes in IMF1 for level3 and the spikes in level2 are very small, it can be easily concluded that damage is located close to level1 sensor.



6(a) **6(b)**

Fig. 6. (a) Acceleration time history responses for level3 (top), level2 (middle), level1 (bottom) respectively (b) IMF1 for level3 (top), level2 (middle), level1 (bottom) for band limited white noise input (modification mass (50gm) placed on level 1 at approximately 4.3 s).

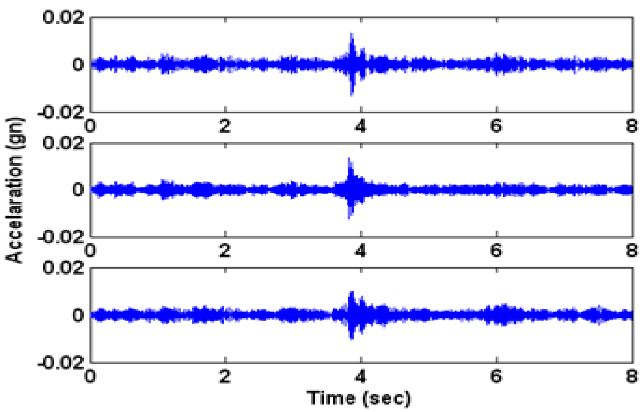
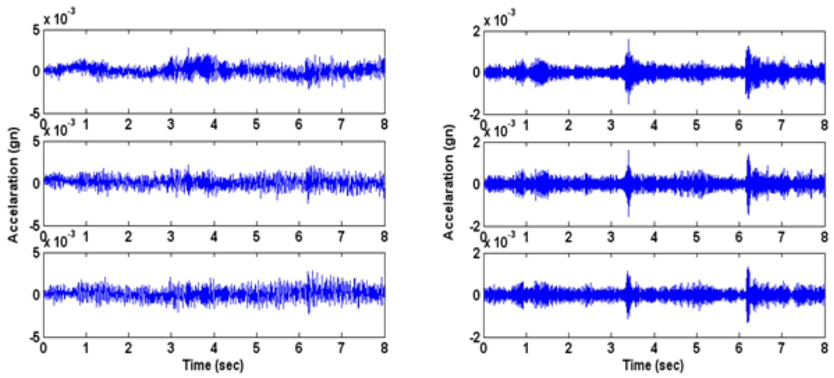


Fig. 7. IMF1 for level3 (top), level2 (middle), level1 (bottom) for band limited white noise input (modification mass 100gm) placed on level 2 at approximately 4.s).



8(a) **8(b)**

Fig. 8. (a) Acceleration time history responses for level3 (top), level2 (middle), level1 (bottom) (b) IMF1 for level3 (top), level2 (middle), level1 (bottom) for band limited white noise input (modification mass (50 gm) placed on level 2 at approximately 3.2 and 6.2 s).

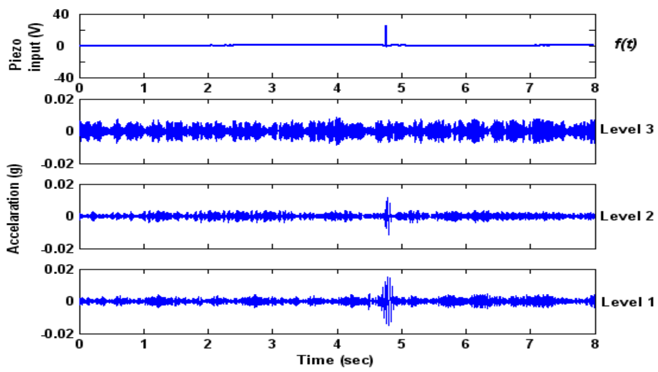


Fig. 9. (a) PZT actuator voltage input time history (b) IMF2 for level3, level2 and level1 for band limited white noise input (PZT actuator energized at 4.8 s to give impulse of 25V).

4.2. Sudden damage detection using EMD method in presence of noise data

The above results have shown that the EMD method is capable of identifying damage presence and location if the structure is monitored on a continuous basis and the damage occurs suddenly (such that the damaging event has a high frequency response). Further, to investigate the sensitiveness of the EMD method in presence of noise to the excitation source is also analysed. Here PZT is used to generate noise, which is added to pollute the response signal. Here different percent of noise (100%, 75%, 50%, 25% and 0%) is added to the excitation source and the response signals are acquired for modification of mass placed at level3 at approximately at 5 seconds.

Figure 10, shows the IMF1 for different percentage of noise added to response signals. When PZT generated 100% noise the respective IMF1 completely insensitive to the damage. For noise 75% and 50% which is present in response respective IMF1 also not that much sensitive. If the 25% noise in response signals respective IMF1 gives the clear spike. Finally if 0% noise added to the response data which gives large spike compare to 25% noise case. From this EMD is capable to identify damage when the response signal has below 40% noise. These cases indicate very low tolerance of the EMD method to the presence of sensor noise.

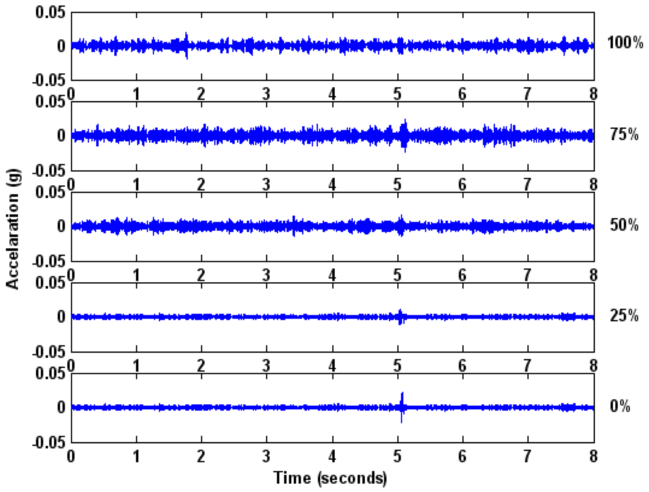


Fig. 10. IMF1 for top level with modification of mass placed approximately at 5 s. noise added to input excitation (a) noise level 100% of original input RMS value (b) 75% (c) 50% (d) 25% (e) 0% (no noise).

5. Conclusions

This paper has presented experimental investigation for detecting the time of damage to multiple levels building structure using empirical mode decomposition (EMD). A three-level structure is employed for the experiments, which is excited using a band limited white noise covering the initial ten frequencies.

- Damage is simulated by modification of mass placed on levels then both the presence and location of damages are determined using IMF1 time history.
- It is also shown damage in response signal introduced by impulse by energizing PZT to 25V also clearly identified using intrinsic mode functions.
- The proposed method is capable to identify damage when the response signal has below 40% noise. From different percentage of noise cases indicate very low tolerance of the EMD method to the presence of sensor noise.
- Due to non-stationary nature of the response signal data have applied the EMD methods to the structure data. The proposed method has a ability for damage detection, which helps it to be used for damage diagnosis. This method could be extended for analysis of other mechanical and civil engineering structures.

Future work has to carry out to check whether any other advanced signal processing techniques will be developed and used to prove even very small instant of damage identify the location and estimate the severity. Develop complete algorithm used for real-time monitoring system for aerospace, structures etc.

References

1. Doebling, S. W.; Farrar, C. R.; and Prime, M. B. (1998). A summary review of vibration-based damage identification methods. *Shock and Vibration Digest*, 30(2), 91-105.
2. Huang, N.E.; Shen, Z.; Long, S.R.; Wu, M.C.; Shih, H.H.; Zheng, Q.; Yen, N.C.; Tung, C.C. and Liu, H.H. (1998). The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *In Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 454(1971), 903-995.
3. Huang, N.E.; Shen, Z.; and Long, S.R. (1999). A new view of nonlinear water wave: The Hilbert spectrum. *Annual Review of Fluid Mechanics*, 31, 417- 457.
4. Zhu, X.; and Law, S. (2006). Wavelet-based crack identification of bridge beam from operational deflection time history. *International Journal of Solids and Structures*, 43(7-8), 2299-2317.
5. Reddy, D.M.; and Swarnamani, S. (2012). Damage detection and identification in structures by spatial wavelet based approach. International *Journal of Applied Science and Engineering*, 10(1), 69-87.
6. Sun, Z.; and Chang, C.C. (2002). Structural damage assessment based on wavelet packet transforms. *Journal of Structural Engineering*, 128(10), 1354-1361.
7. Hou, Z.; and Noori, M. (1999). Application of wavelet analysis for structural health monitoring. *Proceedings of 2nd International Workshop on Structural Health Monitoring*, Stanford University, Stanford, California, 946-955.
8. Hou, Z.; Noori, M.; and Amand, R. St. (2000). Wavelet-based approach for structural damage detection. *Journal of Engineering Mechanics*, 126(7), 677-683.
9. Chen, B.; Chen, Z.W.; Wang, G.J.; and Xie, W.P. (2014). Damage detection on sudden stiffness reduction based on discrete wavelet transform. *The Scientific World Journal*, 1-16.
10. Yang, J.N.; Lei, Y.; Lin, S.; and Huang, N. (2004). Hilbert-Huang based approach for structural damage detection. *Journal of Engineering Mechanics*, 130(1), 85-95.
11. Pines, D.; and Salvino, L. (2006). Structural health monitoring using empirical mode decomposition and the Hilbert phase. *Journal of Sound and Vibration*, 294(1-2), 97-124.
12. Yinfeng, D.; Yingmin, L.; and Ming, L. (2010). Structural damage detection using empirical mode decomposition and vector autoregressive moving average mode. *Soil Dynamics and Earthquake Engineering*, 30(3), 133-145.
13. He, J.; Guan, X.; and Liu, Y. (2012). Structural response reconstruction based on empirical mode decomposition in time domain. *Mechanical Systems and Signal Processing*, 28, 348-366.

14. Bradley, M.; González, A.; and Hester. D. (2010). Analysis of the structural response of a moving load using empirical mode decomposition. *Proceedings of the 5th International Conference on Bridge maintenance, Safety, Management and Life-Cycle Optimization, IABMAS2010*, Philadelphia, 356-363.
15. Vincent, B.; Hu, J.; and Hou, Z. (1999). Damage detection using empirical mode decomposition and a comparison with wavelet analysis. *Proceedings of the 2nd International Workshop on Structural Health Monitoring*, Stanford Univiversity, Stanford, Calif., 891-900.
16. Yang, J.N.; Lei, Y.; and Huang, N. E. (2001). Damage identification of civil engineering structures using Hilbert-Huang transform. *Proceedings of the 3rd International Workshop on Structural Health Monitoring*, Stanford University, Stanford, Calif., 544-553.
17. Garcia-Perez, A.; Sanchez, J.P.A.; Gonzalez, A.D.; Sedaghati, R.; Rios, R.O.; and Troncoso, R.R.J. (2013). Fused empirical mode decomposition and wavelets for locating combined damage in a truss-type structure through vibration analysis. *Journal of Zhejiang University Science A*, 14-9, 615-630.
18. Xu, Y.L.; and Chen, J. (2004). Structural damage detection using empirical mode decomposition: Experimental investigation. *Journal of Engineering Mechanics*, 130(11), 1279-1288.
19. Dushyanth, N.D.; Suma, M.N.; and Latte, M.V. (2016). Detection and localization of damage using empirical mode decomposition and multilevel support vector machine. *Applied Physics A*, 122: 250.
20. Yu, D.H.; and Ren, W.X. (2005). EMD-based stochastic subspace identification of structures from operational vibration measurements. *Engineering Structures*, 27 (12) 1741-1751.
21. Huang, N.E.; Wu, M.-L.; Long, S.R.; Shen, S.S.P.; Qu, W.; Gloersen, P.; and Fan, K.L. (2003). A confidence limit for the empirical mode decomposition and Hilbert spectral analysis. *Proceedings of the Royal Society A - Mathematical, Physical and Engineering Sciences*, 459(2037), 2317-2345.
22. Wu, Z.H.; and Huang, N.E. (2004). A study of the characteristics of white noise using the empirical mode decomposition method. *In Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 460(2046), 1597-1611.