Assessment and localization of active discontinuities using energy distribution between intrinsic modes

Reza Mohammadi Ghazi[1] and Oral Buyukozturk[2]

[1]PhD student Department of Civil and Environmental Engineering Massachusetts Institute of Technology77 Massachusetts Avenue, Bldg 5-336, Cambridge, MA, 02139

[2] Professor, Department of Civil and Environmental Engineering Massachusetts Institute of Technology77 Massachusetts Avenue, Bldg 1-281, Cambridge, MA, 02139

ABSTRACT

A method for localization and severity assessment of structural damages is proposed. The algorithm works based on nonlinear behavior of certain type of damages such as breathing cracks which are called active discontinuities in this paper. Generally, nonlinear features are more sensitive to such damages although their extraction is sometimes controversial. A major controversy is the imposition of spurious modes on the expansion of the signal which needs to be addressed for an effective application and robustness of the method. The energy content of Intrinsic Mode Functions (IMFs), which are the resultants of Empirical Mode Decomposition (EMD), and also the shape of energy distribution between these modes before and after damage, are used for localization and severity assessment of the damages. By using EMD, we preserve the nonlinear aspects of the signal while avoiding imposition of spurious harmonics on its expansion without any assumption of stationarity. The developed algorithms are used to localize and assess the damage in a steel cantilever beam. The results show that the method can be used effectively for detecting active structural discontinuities due to damage.

Keywords: Structural Health monitoring, Active discontinuity, nonlinearity, Normalized Cumulative Marginal Hilbert Spectrum, Energy transfer

INTRODUCTION

Structural Health Monitoring (SHM) can play a significant role in improving the safety of structures as well as extending their life time. Greater complexity, aging, higher operational loads, and severe environmental effects result in more attention to this field. However, after more than thirty years of research, SHM has not been vastly applied in real world structures. Non-unique solutions of inverse problems, complexity, and variety of systems in the real world are the most important reasons that slow down the progress of SHM from research level to application. For instance, several methods have been proposed to detect breathing cracks such as mode shape curvature [1], model updating [2], energy method [3], and nonlinearities [4-7]. All of the aforementioned methods were shown to be effective in a specific problem; however, this does not guarantee their generality. Methods which use numerical models suffer from difficulties of providing a precise model to monitor a system. Most other methodologies are not generalizable since they have been tested on a very specific structure. Moreover, the approach of these papers, typically, is proposing a metric, called a damage index (DI), and then verifying its sensitivity to a certain type of damage. Applicability of the methods with the mentioned approach is possible only after answering the following questions: Is the proposed DI sensitive to the same type of damage, but in different structures? Is the physics behind the DI the best possible representative of damage in the system? If not, how can we improve the method for application in real structures? Is comparing the values of DIs sufficient for characterization of a structure as intact or damaged? A damage detection algorithm is not applicable unless all these questions are answered.

We address the first three questions in this study by proposing several DIs based on nonlinearities due to damage. Other questions will be addressed in future studies. The proposed algorithm in this paper is suitable for detection of a certain type of damage called an active discontinuity. As defined in [8], active discontinuities, such as breathing cracks, are regarded as additional degrees of freedom whose effects on response of the system are above the noise floor. Obviously, activation of a discontinuity depends on the input energy and characteristics of excitation, meaning that the effect of discontinuity on the response of the system may not be discernible from noise under a specific excitation and hence, not activated. Note that even if the discontinuity is activated, it may or may not be detectable using a certain DI depending on its sensitivity to damage and/or how the damage affects the system response. For example, fundamental frequencies of a beam are not changed more than 2% in presence of a breathing crack with the depth of around 20% of the beam's cross section [9], so it turns out to be quite difficult to detect small breathing cracks using a DI based on fundamental frequencies. The problem can be ameliorated by capturing nonlinear effects of damage since nonlinear features of structural response are generally more sensitive to damage [4-7]. On the other hand, a DI should not demonstrate a very high sensitivity to changes in a signal since the results of the algorithm are highly affected by noise and hence, not reliable. Several methods have been proposed based on different types of nonlinearities such as [4-7]. Most of the mentioned DIs suffer from one of these two shortcomings: 1) there is no solid physical interpretation behind the damage index such as those which aim to capture changes in the geometry of signal, 2) subjectiveness which makes it very difficult to use the DIs in complex structures and large sensor networks.

In this paper we try to capture nonlinear effects using an energy-based method. The algorithm not only is sufficiently sensitive to active discontinuities, but also has a concrete physical interpretation behind each DI related to the concept of energy transfer between vibrating modes. There are two requirements essential for retaining the validity of the method; the first is preservation of nonlinearities and the second, prevention of energy leakage of any kind in signal processing. By the use of Empirical Mode Decomposition (EMD) [10], all nonlinearities are preserved in the expansion of a signal in terms of its Intrinsic Mode Functions (IMFs). In addition, there is no leakage of energy due to imposing spurious harmonics on such an expansion, and hence, both requirements are satisfied. The efficacy of the algorithm has been experimentally verified on different structures. The results show that the method can effectively detect active discontinuities due to damage in all cases. In this paper, we present the results only on one simple case which is a cantilever beam consists of three elements.

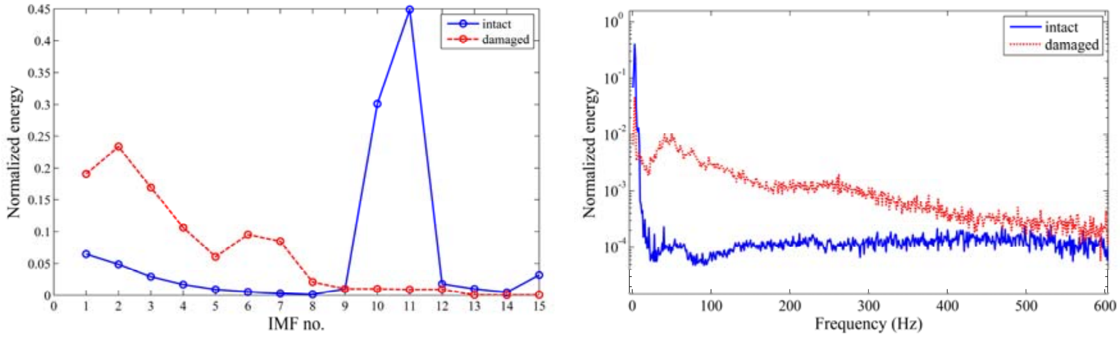
ACTIVE DISCONTINUITIES AND ENERGY TRANSFER BETWEEN VIBRATING MODES

As defined in [8], an "Active Discontinuity" is a type of damage which can affect response of the system such that its effect is discernible from the sensor noise floor. Activation of a discontinuity mostly depends on the severity of damage as well as characteristics of the excitation. It implies that a discontinuity which is activated under a certain excitation may not be activated, and therefore detectable, under a different excitation. Such damage, if activated, generates new modes of vibration or amplify some existing ones. In other words, the damage results in transfer of energy between existing modes or from them to newly generated ones. Based on experiments, this phenomenon showed more sensitivity to damage compared to frequency shift while there is no controversy on the definition of frequency in this concept. In fact, the behavior of active discontinuities is nonlinear and the generated modes by their activation are mostly of high frequency. These high frequency modes change the energy content of other existing ones although they do not affect the dominant response of the system unless the damage is very severe. That is the reason that the energy based method with consideration of nonlinearities is more preferable than other methods which try to capture any kind of change only in frequency response of a system assuming linearity. However, there is a requirement which needs to be satisfied in order to make use of the strengths of the energy method. The requirement is to prevent leakage of energy in any form. Immediately, one can conclude that this condition cannot be always completely satisfied in the Fourier domain, especially in presence of noise, because of spurious harmonics which are imposed on the expansion of the signal. Note that the argument is about the accuracy of method and does not mean to totally disregard Fourier transformation for energy methods. In this paper, we use EMD as the signal processing tool to expand a signal into a set of nonlinear IMFs without any spurious modes and hence, prevent energy leakage. It is also noteworthy that by the "energy of a signal" we mean the norm of the signal or mode function. The norm is the actual energy only if the signal is displacement time history.

Two assumptions are required for development of the algorithm in the simplest form. First, that the input energy and frequency content of excitations are consistent before and after damage. This implies that the algorithm has not been developed for damage detection using arbitrary excitations. There is always a baseline required, but the baseline is calculated using the structure itself without any theoretical assumptions. Secondly, the presence of damage is the only difference between the intact and damaged structure. This assumption is equivalent to consistency of environmental effects.

Normalized Cumulative Marginal Hilbert Spectrum (NCMHS)

With energy methods, we need to express the distribution of energy with respect to a physical quantity. If this quantity is frequency in the sense of Fourier transformation, the distribution is called Power Spectral Density (PSD). Same concept can be defined using EMD and Hilbert Huang Transformation (HHT) and the distribution is called Marginal Hilbert Spectrum (MHS) in this domain. Energy distribution can also be expressed with respect to each IMF as defined in [8]. The latter is useful only if the IMFs are monocomponent. It is less accurate compared to the MHS but computationally more efficient. Fig. 1 shows different energy distributions for empirical data.



(a) (b)

Fig. 1. Different energy distribution curves for same sensor data, a) MHS, b) Energy distribution between IMFs

Working with the non-smooth functions shown in Fig. 1 is not mathematically preferable. Smoothing can be regarded as solution for this problem, but the true physics may be lost. Instead of modifying the curves by smoothing, we propose a more elegant way of solving the non-smoothness problem which is using the cumulative energy distributions rather than the distribution itself. The cumulative function is strictly increasing, smooth, and therefore easy to use, and preserves all physics without imposing any approximation on the problem. In Fig. 2 the cumulative MHS for two tests' data from same sensor on the same structure vibrating under similar excitations are shown. It should be noted that smoothness is used for functions and not sampled data. If we assume that the MHS can be represented as a continuous function, meaning that all frequencies in a specific range have some contribution, then its cumulative summation will be smooth.

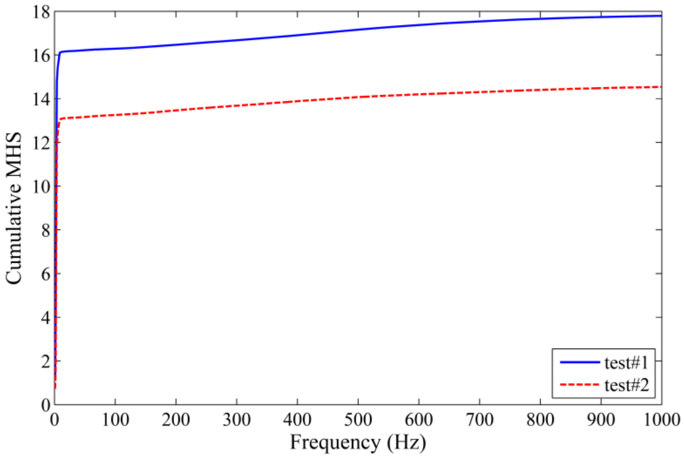


Fig. 2. Cumulative MHS for an empirical data of two tests on an intact structure (same sensor)

Although the cumulative distributions are smooth and monotonically increasing, they still need modification before comparison. As shown in Fig. 2, there is a considerable deviation between two curves although they obtained from the intact structure. The reason is that the total input energies of the tests are different. As a result, comparing these two curves may lead us to a totally wrong deduction which is classifying an intact structure as damaged. Of course, it depends on the comparison methodology; for instance, if we focus only on the pattern of the distribution, they may be consistent. On the other hand, if we measure some other quantity such as the area under the curves the result of the algorithm will be wrong. In order to solve this problem we use the first basic assumption which is the consistency of spectrum and input energy of excitations in all tests. The consistency means that the difference between input energy does not affect the response of the structure; therefore, the effect of this difference can be neglected. As a result, we disregard the difference between input energy and normalize the cumulative function with respect to total input energy. The result is the Normalized Cumulative Marginal Hilbert Spectrum (NCMHS), examples of which are shown in Fig. 3. In this figure, the NCMHS for a set of empirical sensor data consisting of two tests on an intact structure and one for the same structure with damage are illustrated. In contrast to cumulative curves, the difference between Normalized Cumulative curves of the intact structure is not significant while the deviation between the damaged and intact structures is quite obvious. This procedure is generalizable to any other energy distribution such as the PSD to obtain the Normalized Cumulative PSD (NCPSD) or to energy distribution between IMFs as well, provided the assumption is satisfied.

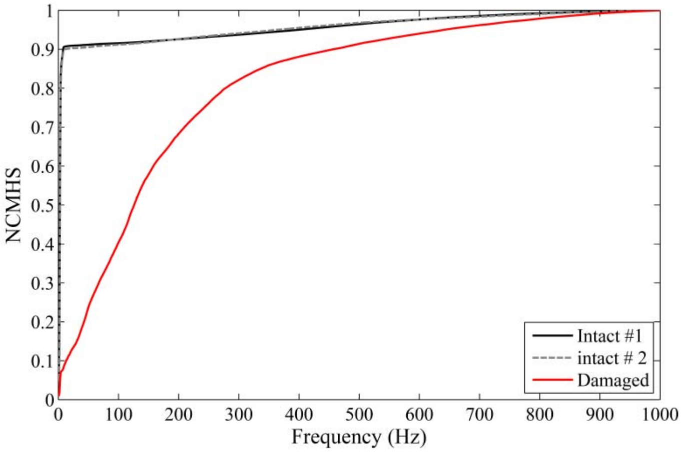


Fig. 3. NCMHS of empirical data consists of two tests on an intact structure and one test on the same structure with damage (same sensor)

DAMAGE INDICES

In previous section, it was shown that the NCMHS can be regarded as a reliable signature for the intact state of a structure under excitations with consistent spectra and input energies. In addition, it was shown that the NCMHS for the certain type of damages, active discontinuities, deviates from that signature due to the change in the pattern of energy distribution. Some, out of many, possible ways of quantifying this deviation are presented in this paper. We also do not restrict ourselves to use only the normalized cumulative curves since some quantities, such as the mean frequency, make sense only if the original curves are used. The first DI is defined as

$$DI_1 = \frac{\sum_i |A_i|}{A_{BL}} \tag{1}$$

where A_i is each portion of the area between NCMHS of the structure we are testing and the baseline NCMHS (**Fig. 4**); A_{BL} is the area under the baseline NCMHS. In this study, we defined the baseline using median of tests on intact structure, using only the sensor data and without any theoretical assumption. The median is chosen because of its robustness with respect to outliers. The numerator in eq. (1) is the absolute value of the whole area between two curves and its physical interpretation is the total energy transfers between different modes. The denominator is only for normalization which provides a dimensionless DI in the range of zero to one. Similarly, another measure of energy transfer can be defined as

$$DI_2 = \frac{\left|\sum_i A_i\right|}{A_{BL}} \tag{2}$$

In this DI, some of the A_is are cancelled out if one curve oscillates around the other. Indices for comparing these curves are not restricted to eq. (1) and (2). Other possible methods are the ones which are used for comparing cumulative probability distributions. Of course, some of them cannot be interpreted physically even if they work well. For instance, Kolmogorov–Smirnov distance can be used and it shows a good sensitivity to damage; however, it has no solid physical interpretation.

As it mentioned before, some DIs should be defined using the original MHS. Again, based on the assumption for consistency of input energy, we can normalize the MHS to make a more meaningful comparison. Using normalized MHS one can define

$$DI_3 = \frac{\overline{F}}{\overline{F}_{BL}} \tag{3}$$

where the $\overline{F}$ is the mean frequency of MHS, $\overline{F}_{BL}$ is the mean frequency of baseline MHS. This DI can be interpreted as a measure of change of fundamental modes (frequencies), but not in Fourier domain. It tells us where the accumulation of energy is.

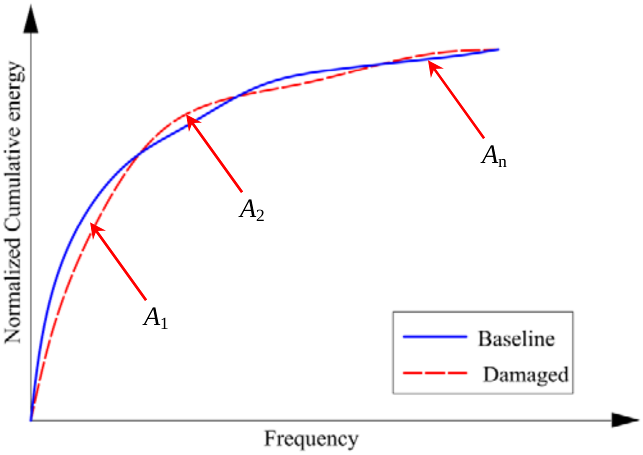


Fig. 4. Parameters for comparing NCMHS

SEVERITY ASSESSMENT

After localization of damage, the same concept of energy transfer between modes can be used for severity assessment of the active discontinuity. Stiffness reduction and generation of nonlinear high frequency vibrating modes are two main effects of such damages on the behavior of structure. The first effect dominates when the damage severity is low. In this case, the rigidity of the structure around the damage is high enough such that it prevents the generation of higher modes; therefore, the fundamental frequencies shift due to the energy transfers into low frequency modes. If the severity is high, the later effect dominates and the energy of high frequency modes will be increased.

Capturing this phenomenon is easier if the distribution of energy between IMFs is used rather than the MHS. In fact, the high resolution discretization of frequency bands in the MHS hides these tiny effects. As shown in Fig. 5, the cumulative energy distribution in the case of major damage lays above the intact case. The reason for the high slope of the curve near the high frequency IMFs in the damaged case is the accumulation of energy in these modes. For the minor damage, on contrary, the slope of the curve is high near the low frequency IMFs and hence, it is below the baseline.

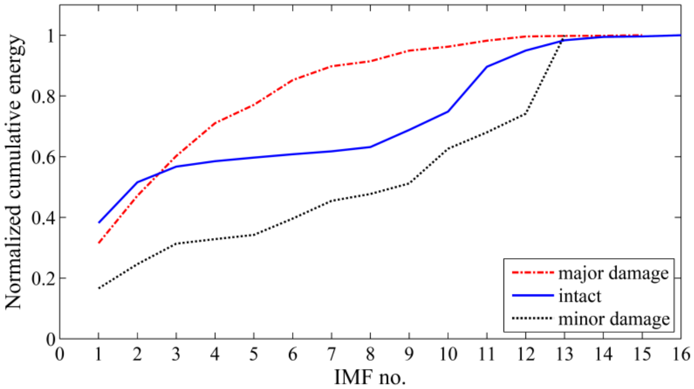
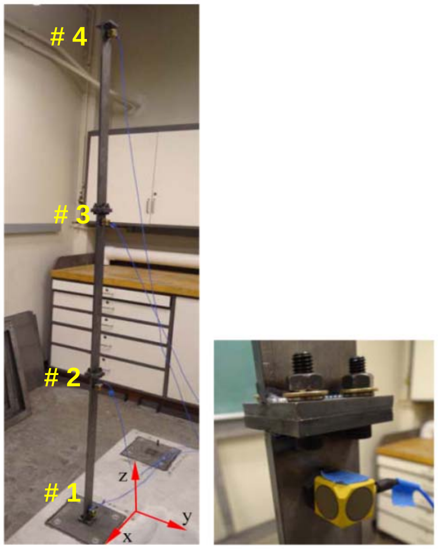


Fig. 5. Comparison of normalized cumulative distribution of energy between IMFs

EXPERIMENTAL SETUP

In this study, we try to capture some nonlinear phenomena which are very difficult to simulate numerically. Therefore, experimental tests have been chosen as a more rigorous way of verification of the algorithm. The algorithm has been verified for different structure and the one which is presented in here is a cantilever beam consisting of three elements bolted together as shown in Fig. 6. The bolts are completely tightened in the intact structure such that the end plates of the elements are clamped. A triaxial accelerometer also is attached in the vicinity of each connection. Free vibration is chosen as the excitation in order to reduce the complications of dealing with different excitations and focus only on the efficacy of the algorithm.



(a) (b)

Fig. 6. Experimental setup; a) Cantilever beam consists of three elements; b) Accelerometer attached near a connection

The structure was tested under four damage scenarios which are listed in Table 1. In the case of minor damage, two bolts removed in one side of the connection while two other bolts were completely tightened. For the major damage, all four bolts were slightly loosened such that the structure did not lose stability. The sampling rate was chosen to be 3 kHz in order to capture the higher modes as precisely as possible.

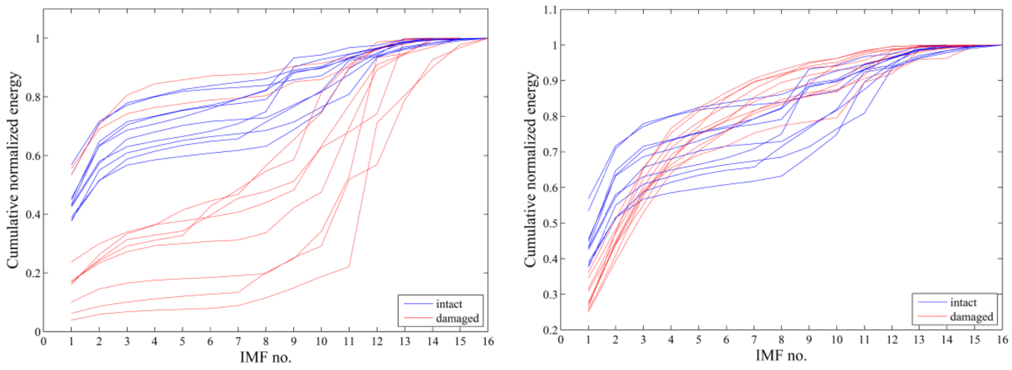
Table 1. Different damage scenarios

Damage scenario	Description
1	Minor damage at node #2
2	Major damage at node #2
3	Minor damage at node #3
4	Major damage at node #3

RESULTS

The sensor data in z direction (Fig. 6), perpendicular to the discontinuities, was analyzed. To assess the sensitivity of the algorithm to data length, two signal lengths were investigated: five seconds of data, and two seconds of data for comparison. In this paper, only the results of the later one are shown because there is no considerable difference between them. Moreover, multiple tests were conducted for each damage scenario, but, because the results are similar, for the sake of brevity only one of them is illustrated.

The NCMHS for all tests and both minor and major cases are shown in Fig. 7. As expected, the curves are above the intact case in the case of major damage due to transfer of energy to high frequency modes and vice versa for minor damages. The damage index in all cases, which is shown in Fig. 8, has the highest value for the sensor at the node adjacent to the damage. It should be noted that for minor damage, the two end plates of elements in the connection where the damage presents are completely clamped in one side and there is no visible gap. However, the algorithm can effectively detect and also assess the severity of damage by considering nonlinearities in a very simple way.



(a) (b)

Fig. 7. NCMHS fore the sensor at node#3; a) minor damage; b) major damage

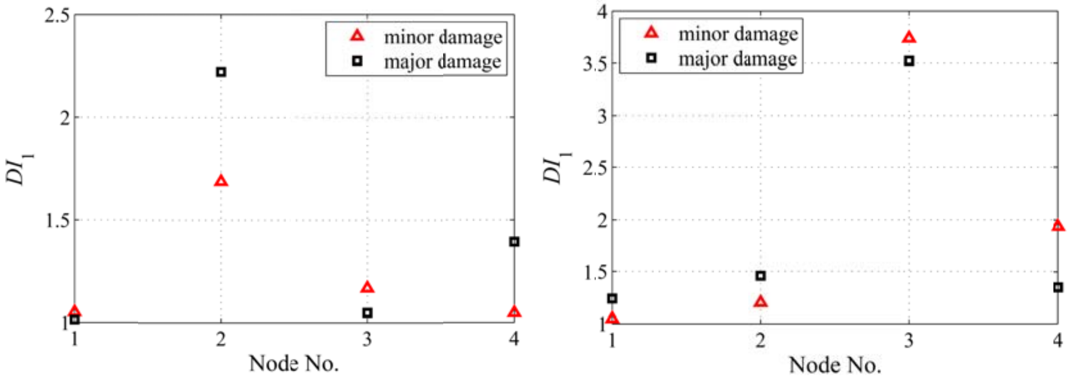


Fig. 8. DI_1 for a) damages at node#2 and b) damages at node#3

CONCLUSIONS

In this study, an algorithm for localization and assessment of certain type of damages named active discontinuities was proposed. Breathing cracks and loosened bolts in a connection are examples of this type of damage. Activation of such discontinuities results in the generation of new vibrating modes which are nonlinear and mostly have high frequency content. Assuming the same excitations for both intact and damaged structures, the distribution of input energy between the modes of vibration is changed due to damage. In other words, active discontinuities result in energy exchange between existing modes and newly generated modes due to damage. In order to capture this effect, several conditions should be satisfied. First, the spectrum and input energy of the excitation for both intact and damaged structures should be consistent. Second, any leakage of energy should be prevented for the method to be reliable. By using EMD for the decomposition of a signal, nonlinearities are preserved and all requirements for the second aforementioned condition is satisfied. To capture the nonlinearities after decomposition, we use the distribution of energy between different modes of vibration which can be expressed in different ways. MHS and distribution of energy between IMFs are examples of such distributions. Two modifications are accomplished on the energy distribution to make it easier to analyze them. The modifications are, first using cumulative energy distribution and the second, normalization with respect to total input energy. These modifications give us well-behaved monotonically increasing curves, named the NCMHS if the MHS is used as the original distribution, which can be regarded as a signature for the system by preserving all physics.

Among several methods of comparing the normalized cumulative curves, we used the area between NCMHSs for the damaged structure and the baseline. This index, in contrast to other pure mathematical indices, has a solid physical interpretation which is the total transferred energy between modes. Stiffness reduction and generation of nonlinear high frequency modes are two important effects of active discontinuities. These effects, which manifest themselves in the shape of the energy distribution, can be used for severity assessment of the damage. The energy distribution between IMFs, because of low resolution, magnifies the accumulation of energy in certain frequency band and hence, more appropriate for severity assessment. In the case of major damage, the energy is transferred to high frequency modes and the corresponding curve lays above the baseline. The opposite is true for the minor damages.

The efficacy of the algorithm is experimentally verified by testing a cantilever beam consisting of three elements which are bolted together under four damage scenarios. The results show that the algorithm can effectively detect and localize active discontinuities and also assess their severity even in the case of minor damages. The algorithm provides quantitative damage indices by capturing nonlinearities in a simple and effective manner.

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