Development of robust metric based on cumulative electrical power for electromechanical impedance based structural health monitoring

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Abstract

Electromechanical impedance (EMI) based techniques have been proposed for structural health monitoring due to their sensitivity to low levels of damage. Most of the work in the EMI technique depends on the change in the admittance signature of the structure in the healthy and damaged state. Several metrics have been proposed to quantify this difference in the signature. Most common being root-mean square difference (RMSD), mean absolute percentage deviation, correlation coefficient etc. As the admittance signatures has several troughs and peaks, the statistical metrics are not robust and often show false detection due to ambient changes and measurement noise.

Thus, this paper proposes a novel index for the damage detection using the EMI technique based on the cumulative electrical power. The frequency v/s resistance or conductance plot is used for calculating the normalized cumulative electrical power (NCP) of the system. The NCP curve is a monotonically increasing function and hence robust for statistical comparison. The cumulative power curve is then used to develop three different indices comparing the amplitude difference (RMSD of the NCP curves), difference in the area under the NCP curve as well as the modified Frechet distance between the NCP curves. The performance of these indices are compared with the RMSD index which has been commonly used. The comparison is carried out on four different structures and show very encouraging results. In addition to the experimental validation, sensitivity studies have been carried out on an analytical signal. It is seen that the Frechet distance based index is a robust indicator for damage detection and minimizes the false detection under variety of conditions affecting the EMI signature.

Keywords: electromechanical impedance (EMI), normalized cumulative electrical power (NCP), damage detection, structural health monitoring (SHM), Frechet distance

(Some figures may appear in colour only in the online journal)

1. Introduction

Health monitoring of structures has the potential to reduce the life-cycle costs of structures. This economic potential has resulted in structural health monitoring (SHM) techniques being developed in wide range of applications including civil infrastructure such as buildings, bridges, dams etc aerospace...
structures, wind turbines, oil and gas platforms etc. Several SHM techniques making use of different damage sensitive features have been developed based on the specific application demands. The most commonly used techniques are the vibration based SHM techniques [1], strain based techniques [2], guided waves (GW) based techniques [3], electromechanical impedance (EMI) based techniques [4] etc.

The vibration based SHM techniques were among the first to be developed and have found applications in concrete structures as well as metallic and composite structures. These techniques are typically low cost and suitable for global level damage detection and isolation. Unfortunately these techniques are insensitive to small and local damage scenarios which too if left undetected can put the structure at risk. This risk is particularly severe for composite structures and concrete structures as these materials are less damage tolerant than metallic structures. Hence local level damage detection techniques such as local strain monitoring, GW and EMI have been proposed for these structures [5–7]. The strain monitoring techniques earlier employed the resistance strain gauges but the survivability and the repeatability of the sensors was an issue. The advent of the fibre optic sensors overcame some of the issues but their cost is still prohibitively high thus limiting their applicability in structures. The GW based techniques allow assessment of the structure over a large area with relatively few sensors especially in metallic structures. But these techniques are only useful for thin specimens. Even in thin specimens, where the structure has a complex geometry and the material is anisotropic the signal processing is indeed a challenge. Hence, the search for a better SHM technique is still ongoing.

Several researchers have shown the suitability of the EMI technique for the detection of damage. Excellent reviews of the use of this technique have been periodically published which shows the research interest the method enjoys [6, 8–10]. These reviews not only report the state of the art but also identify the challenges faced by the technique. The EMI technique typically works in a high frequency range and is able to detect small levels of local change. The EMI technique typically makes use of piezo-ceramic transducers (PZT) to actuate the host structure harmonically in the presence of electric field (varying voltage signal) to produce a structural response comprising of peaks and valleys on an admittance vs. frequency plot, which is known as electromechanical admittance signature. The change in this signature may be quantified and used for the detection of the condition of the structure [10]. In addition to the admittance signature, in literature it is a common to use the derived quantities from admittance such as impedance, resistance and conductance. This paper follows this approach and uses the conductance and resistance signatures for the processing.

A significant amount of work has been carried out in order to develop a robust metric for quantifying the change in the admittance signature such as root mean square deviation (RMSD), mean absolute percentage deviation, covariance and correlation coefficient [11]. These metrics were introduced over 10 years ago and still are popular in use. Several variations of the RMSD metric such as RMSDk [12], and other metrics mentioned by Martowicz et al. [13] have been investigated and continue to attract interest from researchers. Several researchers have also reported comparative studies of these metrics [14–17] with different conclusions based on the application at hand, the type of damage, the frequency range chosen etc. Apart from these four metrics few researchers have proposed additional statistical parameters such as the damage index proposed by Hu et al. called the damage index-Ry/Rx [17], the chessboard distance [18], united mechanical impedance [19], ellipse damage index [20], the Mahalanobis distance [21] etc. These metrics statistically compare the signal in the frequency domain in the healthy and damaged condition. The typical signal is full of peaks and troughs as shown in figure 1.

For such complex shapes the statistical comparisons are prone to be unstable. This instability stems from minor changes in the ambient conditions as well as measurement errors. The statistical metrics are known to perform better where the signal can be presented in analytical form and hence was a motivation to develop the proposed approach. The current paper develops a quantity (normalized cumulative electrical power (NCP)) based on a more stable presentation of the derivatives of the admittance (conductance or resistance). It then develops three metrics for the quantification of the difference in the NCP curves due to damage. The metrics developed compare the shape of the curves, the difference in the areas under the curve as well as the root mean square difference (RMSD) in the NCP curves. The performance of the newly developed metrics is compared with the RMSD metric (equation (1)) which has been the most commonly employed metric for EMI based SHM.

\[
RMSD = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - Y_0)^2}{\sum_{i=1}^{n} (Y_0^2)}}
\]  

where, \(Y_i\) represents the reference signature (conductance or resistance) of the PZT at the \(i^{th}\) measurement point and the \(Y_0\) represents the corresponding signature in the damaged condition at the \(i^{th}\) measurement point.

The new metric is applied on four different test specimens made from different materials in different frequency ranges. Based on the obtained results, it is seen that the newly developed shape-based metric outperforms the RMSD. The improved performance is due to the stability of the monotonically increasing NCP curve as compared to the conductance or resistance plots.

The novelty of the paper stems from use of statistically stable presentation of the admittance as well as the novel quantification metrics which have not been employed for EMI based SHM to the best of author’s knowledge. The analytical studies as well as the detailed experimental investigations indicate that the proposed metric is indeed robust and performs better than the RMSD technique. The RMSD technique has been used to compare the performance as it has been the most commonly employed damage metric for EMI based studies as reported by Na et al. [10], and hence has been studied for a wide range of applications, frequency ranges, and conditions.
2. Theoretical background

As mentioned earlier, the statistical comparisons are more robust for functions which are easier to present analytically. Monotonically increasing or monotonically decreasing functions are fairly simple functions and are ideal for applying the statistical metrics. Hence in order to obtain a monotonically increasing function, the metric NCP was used. If the resistance signature is used, the metric obtained is the inverse of the electrical power while if conductance signature is used the metric obtained is the total electrical power. It should be noted that although the quantities obtained, i.e. the electrical power or its inverse are physically significant, these quantities are used only for the statistical comparison. Hence in the further discussions the term NCP is used for both the resistance based metric or the conductance based metric. The electrical power is normalized so as to allow comparison between the different damage scenarios irrespective of the input voltage. The NCP is loosely inspired by the normalized cumulative marginal Hilbert spectrum [22, 23]. The NCP can be calculated from the conductance or resistance signature vs. frequency plot by equation (2). The NCP for the resistance and conductance plots shown in figure 1 are presented in figure 2

\[ NCP(f) = \frac{\sum_{f=f_{\text{min}}}^{f_{\text{max}}} (Y_i)}{\max(\sum_{f=f_{\text{min}}}^{f_{\text{max}}} (Y_i))} \]  

where, \( f_{\text{min}} \leq f \leq f_{\text{max}} \), \( f_{\text{max}} \) and \( f_{\text{min}} \) correspond to the frequency band of choice and max corresponds to the maximum of the summation used for normalization.

The monotonically increasing NCPs for healthy and damaged scenarios can then be compared using different comparison metrics. The metrics commonly used can be classified as the amplitude based metrics and the shape based metrics. The amplitude based metrics quantify the vertical difference between the curves to be compared. Two metrics may be developed on this principle such as the difference in area under the curves (\( DI_1 \)) [24] and the RMSD between the two NCP curves (\( DI_2 \)). The metrics \( DI_1 \) and \( DI_2 \) may be calculated by equations (3) and (4):

\[ DI_1 = \frac{\sum |A_d - A_0|}{A_0} \]  

where \( A_d \) and \( A_0 \) correspond to the area under NCPs for the damaged and health cases respectively.

\[ DI_2 = \sqrt{\frac{\sum_{i=1}^{n} (NCP_d(i) - NCP_0(i))^2}{\sum_{i=1}^{n} (NCP_0(i))^2}} \]  

The amplitude based metrics only compare the vertical distance and as such there is no notion of the shape of the curves. For comparing the shape of the curves, a metric similar to the Frechet distance was proposed. The Frechet distance gives the minimal distance between the two points on the two curves where the rate of travel of the points on either curve may not be uniform. In order to remove the scaling effects both axes of the curves are rescaled in interval [0,1]. The points on the rescaled curves can be represented by a set of 2D points given by equation (5) [25].

\[ p_i = \{(f,NCP^{(i)}(f)) \mid f,NCP \in [0,1] \} \]
Figure 2. Normalised cumulative power (NCP) metric. (a) Conductance. (b) Resistance.

For a given point $f$, the distance between the curves is found as the shortest Euclidean distance between the specific coordinate on curve $p_i$ and all co-ordinates on $p_j$ given by 6.

$$\delta(i,j) \equiv d_{\text{min}}((f,NCP^{(i)}(f)), p_j)$$

The difference between the two curves is then computed by integrating the difference between the curves in order to find the $DI_3$ given by equation (7)

$$DI_3 = \sqrt{\int_0^1 \delta(i,j)^2 df + \int_0^1 \delta(j,i)^2 df}$$

The three metrics developed are compared with the RMSD metric for raw conductance and resistance signatures in the subsequent sections. The performance of the metrics is compared for four different structures. The experimental setup and the details of the four structures are provided in the next section.

2.1 Threshold determination

Any metric will show some level of change for any two measurements even under same conditions due to the measurement noise and other uncertainties. In order to determine the presence of damage, the change in the metric should exceed a certain value (threshold). This threshold value needs to be determined based on the sensitivity of the metric and confidence of the measurements, robustness of the metric as well as the costs associated with the false detections [26]. For the purpose of the study, the threshold is determined by calculating the change in the particular metric for two measurements under healthy condition. It is assumed that the two measurements under the same states capture the different uncertainties inherent in the measurements. Similar approach was used by Moll [27] and Singh et al [28] to determine the threshold. A point to note is that the developed metrics are compared to the baseline for the same sensor. Each sensor due to the sample, the bonding conditions, its position and difference in the sensor properties will have different sensitivities. But the main aim of this paper is development of new metric as a result, for the sake of simplicity, the threshold value is taken as the maximum value of the change in the metric for all the sensors. This threshold value was chosen, as it represents the highest change in the metric due to the ambient condition changes. This highest value allows us to incorporate the uncertainties in the ambient condition changes as well as the stability and the repeatability of the sensors and the equipment. The authors acknowledge that the determination of threshold this way is simplistic and further work needs to be done to statistically determine the appropriate threshold.

3. Experimental setup

The EMI measurements were conducted using piezoelectric sensors. The sensors were in the shape of discs with 10 mm diameter and 0.5 mm thickness. They were manufactured by CeramTec from SONOX P502 material [29] or Noliac NCE51 [30] material as stated for each sample. In the research the HIOKI IM3570 analyser was used. Four structures studied were:

(a) Glass fibre reinforced plastic (GFRP) plate with 4 SONOX sensors
(b) GFRP beam with 1 SONOX sensor
(c) Aluminium plate with 9 SONOX sensors (3 sensors analyzed in this paper)
(d) Adhesive bonded carbon fibre reinforced plastic (CFRP) beams with 2 NCE51 sensors.

The GFRP plate (500 mm × 500 mm × 3 mm) made of 8 layers of woven GFRP was instrumented with four sensors
(P1–P4) placed in corners of a square 260 mm away from each other. It is important to underline that the initial condition of the sensor P1 was different from the other three sensors (P2, P3 and P4). During the manufacturing stage of the plate a Teflon insert (10 mm × 10 mm) was put between the second and third layer of the sample at the location where later the P1 sensor was glued. The reference measurements were taken (HS1 and HS2). Next, impact damage was introduced in the structure. The impact was made at the energy of 30 J with a projectile with a spherical end. In total four impacts were made near sensor P2 and P3. After each impact the EMI measurement was taken. The details of the specimen and the nomenclature of the scenarios can be seen in figure 3. The measurements in the frequency range from 1 kHz to 1.5 MHz with a frequency step of 200 Hz were used for the study.

The eight layered GFRP beam with dimensions: 500 mm × 95 mm × 3 mm was studied with one piezoelectric sensor. The damage in the form of delamination was introduced and later enlarged with a chisel. The main dimensions (horizontal × vertical) of the delamination at each stage were following: 10 mm × 5 mm (Scenarios S11 and S12), 20 mm × 10 mm (Scenarios S21 and S22) and 30 mm × 10 mm (Scenarios S31 and S32). Before introducing the delamination two referential measurements were made(SH1 and SH2). Similarly, after each stage of delamination two measurements of EMI signatures were taken. The measurements were carried out over the frequency range from 1 to 100 kHz with a frequency step of 10 Hz. The details of the specimen can be seen in figure 4.

The third structure investigated was an aluminium plate of dimensions 1000 mm × 1000 mm × 1 mm. The plate was instrumented with nine sensors based on an optimization strategy for GW strategy reported in [31]. For the purpose of this study only three sensors near the damage area were used. The EMI signatures of the other sensors were not affected by the holes as they were too far from the damage. The chosen sensors are at an equal distance (223 mm) from the introduced damage. The simulated damage in this case was drilled hole with three diameters 5 mm (Scenarios D11 and D12), 8 mm (Scenarios D21 and D22) and 10 mm (Scenario D31) at the location shown in figure 5. Firstly the referential conditions (H1 and H2) were measured and after introducing each hole two sets of measurements were done. The measurements were carried out over the frequency range from 5 kHz to 2 MHz with a frequency step of 200 Hz.

The fourth structure was a CFRP beam. This beam consisted of two dogbone samples bonded together. Dogbone samples are utilised in tensile strength tests. Each sample was made out of eight reinforcing layers with orientations [0/90/45/135], with total thickness 1.5 mm. Samples were bonded together using two part epoxy glue PRO WELD® QUICK Pro Seal bonding agent. Sample was supported at one side creating cantilever beam. Beam was equipped with two piezoelectric transducers (PZT1 and PZT2) located above and below bonded area. The two sensors were used to investigate the repeatability of the measurements and the effect of damage on either sides of the bond. Transducers were in the form of discs with diameter 10 mm and thickness 0.5 mm, made out of NOLIAC NCE51 piezoelectric material. Transducers were bonded using cyanoacrylate bond agent. Four damage scenarios were investigated as shown in figure 6. First scenario (Dam1) was in the form of 1 mm wide and 40 mm long notch in bonding layer. Second and third scenarios (Dam2 and Dam3) were triangular disbonds with lengths of edge 10 and 20 mm respectively. Fourth damage scenario was disbond with
Table 1. Nomenclature and description of the damage scenarios for the four structures.

| Structure 1: GFRP plate | Structure 2: GFRP beam |
|-------------------------|------------------------|
| HS1: Reference repetition 1 | SH1: Reference repetition 1 |
| HS2: Reference repetition 2 | SH2: Reference repetition 2 |
| DS1: 30 J impact at 130 mm from sensor 2 | S11: Delamination 10 mm × 5 mm |
| DS2: DS1 + impact at 130 mm from sensor 2 | S12: S11 repetition |
| DS3: DS2 + impact at 55 mm from sensor 2 | S21: Delamination 20 mm × 10 mm |
| DS4: DS3 + impact at 25 mm from sensor 2 | S22: S21 repetition |

| Structure 3: Aluminium plate | Structure 4: CFRP beam |
|-----------------------------|------------------------|
| H1: Reference repetition 1 | Hea1: Reference |
| H2: Reference repetition 2 | Dam1: notch 1 mm × 40 mm |
| D11: Circular hole \(\phi = 5 \text{ mm}\) | Dam2: Dam1 + 10 mm triangular disbond |
| D12: D11 repetition | Dam3: Dam1 + 20 mm triangular disbond |
| D21: Circular hole \(\phi = 8 \text{ mm}\) | Dam4: disbond 40 mm × 20 mm |
| D22: D21 repetition | |
| D31: Circular hole \(\phi = 10 \text{ mm}\) | |

dimensions 40 mm × 20 mm. All damage scenarios were created without changing support conditions. EMI measurements were performed in the temperature 26±1 °C. The measurements were carried out over the frequency range from 1 to 200 kHz with a frequency step of 10 Hz.

The table 1 presents the different damage scenarios, their nomenclature and description for the four structures which are investigated.

4. Experimental results

The performance of the three metrics is compared with the RMSD for four different structures. For the case of the GFRP plate the figure 7 shows the EMI conductance and the NCP plot for the different damage scenarios. As can be seen the conductance signature has several troughs and peaks while the NCP curve is monotonically increasing which augurs well for the statistical comparison. For the computation of the metrics the entire frequency range (1 kHz–1.5 MHz) was used. The magnified insets in figures 7(a) and (b) are to clearly show all the plots.

The four metrics based on the resistance and conductance signatures are shown in figures 8 and 9 respectively. Although conductance based metric has physical relevance and correlation to power. It is known that the resistance and the conductance measurements have different sensitivities in different frequency ranges (conductance at higher frequencies and resistance at lower frequencies). Hence the suitability of the metric for conductance and resistance both has been investigated.

Firstly, the plots for the indices based on the conductance and resistance are very similar. This in turn points towards the robustness of the indices irrespective of the quantity chosen for the analysis. For further discussion, only the conductance based metric due to its physical equivalence to the electrical power will be discussed unless otherwise stated.
It is important to notice that the damage index corresponding to sensor 2 is the highest for all four metrics in damage scenarios DS2, DS3 and DS4. But there are some other key observations which can also be made in order to determine the efficacy of the indices. If the threshold for damage detection is determined as the highest change in the index for the healthy conditions, then the RMSD index only provides detection in damage scenario DS4. On the other hand the $DI_1$ index provides accurate damage detection for all the damage scenarios. The damage indices $DI_1$ and $DI_2$ show false detection for scenario DS1 but perform well for the scenarios DS2, DS3, DS4. Another key observation which can be made is that the bar corresponding to the sensor 2 for damage scenarios DS2, DS3 and DS4 for the RMSD index and the $DI_3$ is increasing while for $DI_1$ and $DI_2$ is decreasing. The bar is expected to increase as the damage scenarios are corresponding to increase

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**Figure 7.** (a) Conductance signature of all damage scenarios for sensor 2. (b) NCP for all damage scenarios of GFRP plate for sensor 2.

**Figure 8.** Comparison of the four damage indices based on resistance signature for structure 1 (GFRP plate) in the frequency range 1 kHz to 1.5 MHz.

**Figure 9.** Comparison of the four damage indices based on conductance signature for structure 1 in the frequency range 1 kHz to 1.5 MHz.
in the damage severity. So, it can be concluded that the damage severity is better reflected by the RMSD index and the $DI_3$. Another observation is the height of the index corresponding to sensor 3. The index is expected to grow from DS1 to DS2 but should ideally remain constant for the other damage scenarios. This is due to the fact that the subsequent impacts are made at a location further away from the sensor 3 and as such the sensor 3 is not expected to be very sensitive to those changes. Thus looking at the successful damage detection and isolation in all the damage scenarios, the increasing values of the index corresponding to the increasing damage and the stability of the index for sensor 3, the $DI_3$ index performs better than the RMSD index. The performance of the indices $DI_1$ and $DI_2$ is intermediate as they do detect the damage scenarios DS2 and DS3 as well, but give false detection for DS1. Also they do not reflect the severity of damage as well as the RMSD and the $DI_3$ index.

For the other validation cases, the ability of the damage indices to determine the extent of damage was investigated. A simple composite beam with increasing severity of damage was investigated. The comparative plots for the indices are shown in figure 10. It can be seen that all indices show a uniform trend of increasing value of index with increase in the extent of damage. It should also be noted, that the value of the index is greater than that for the baseline condition in all the cases. Another observation which can be made is that there is a small deviation in the indices for the two measurements of the same condition. Each of the measurements presented is an average of 50 measurements and hence the measurements are deemed to be statistically stable. The deviation in the value for the same condition is due to the uncertainties in the measurement and is similar in value to the index value corresponding to the SH2 measurement. Based on this figure it can be concluded that all the indices perform equally well for this application.

In order to qualitatively compare the performance of the indices for assessing the extent of damage, one more validation case was undertaken. In addition to the composite plate, the performance of the methodology was investigated for an aluminium plate. The results for the three sensors under six different damage scenarios are shown in figure 11. As can be seen, the damage is detected for all three sensors in all the damage scenarios for all the indices. Another observation that can be made is the increasing value of the index $DI_3$ with the increase in the hole size. Similar trend is also seen for the RMSD index except for the anomaly seen for sensor 4 for scenario D12. This is due to a significant shift in the conductance signature for the D12 measurement over the entire frequency range as shown in figure 12. In the experience of the authors such shifts are often seen due to ambient condition changes or additional tension in the wires connecting the PZT sensors. Although these shifts can be compensated through detrending, the decision of this detrending makes automated damage assessment of structures more difficult. Hence an indicator which is more robust to such abrupt changes is more desirable. The damage index $DI_3$ is robust in such situations. It should be noted that no consistent trend can be seen for the indices $DI_1$ and $DI_2$ and hence are not considered ideal for the determination of damage severity. Due to the inconsistency in the results for the detection of the severity of damage, one more test case was investigated.
Figure 12. Comparison of part of conductance signatures for sensor 4 for aluminium plate.

Figure 13. Comparison of the four damage indices based on conductance signature for bonded CFRP beams in the frequency range 1 to 200 kHz.

Figure 14. Comparison of the four damage indices based on conductance signature for GFRP plate in the frequency range 5 to 100 kHz.

with the two dog bone CFRP beams bonded together. The figure 13 shows the plots for the four indices. As can be seen the RMSD indicator does not see an increasing trend, on the other hand $DI_1$, $DI_2$ and $DI_3$ show a clear increasing trend with the increase in the damage. The RMSD indicator does show increase in the value of indicator but the trend is not apparent between cases Dam1 and Dam2 for sensor 1 and Dam2 and Dam3 for sensor 2. It should be noted that $DI_1$ and $DI_2$ have been plotted in log scale to show comparable heights of the metrics. As a result, the Dam1 scenario for sensor 1 shows a small increase. The aim of the performed experiments was to minimize the changes in the ambient conditions between two measurements and hence the measurements were carried out in quick succession. As a result the measurement for the same condition were not repeated. As a result the threshold value for damage detection was not identified. Hence the present case should be considered only for the validation of the ability of the metrics for detecting increasing damage.

Based on the results presented in figures 10, 11 and 13 it is apparent that $DI_3$ performs satisfactorily in all three cases. The RMSD metric performs well for the GFRP plate but fails in the Aluminium plate and the CFRP beams due to the changes EMI in the spectrum such as vertical shifts. The metrics $DI_1$ and $DI_2$ show a trend in the case of GFRP plate and CFRP beams but not in the case of aluminium plate. There are several sources of the uncertainties for this discrepancy, although, the authors believe that the difference is most likely due to the measurement noise (extra peaks) in the metal measurements seen even after the smoothing (moving average over 50 points). Hence, it is concluded that the $DI_3$ is a suitable metric for the identification of damage severity and performs better.
than the RMSD technique for raw conductance and resistance signatures.

5. Sensitivity studies

5.1 Stability over different frequency

The previous section compared the performance of the four indices for damage detection on four different structures. The four structures were part of different studies and hence the frequency ranges for the measurements were different. In order to determine the effectiveness of the proposed methodology comparison of the metrics for the four structures over the same frequency range was undertaken. The common frequency range for all the samples was 5 to 100 kHz and was used for the analysis.

In figure 14 it can be seen that DS2, DS3 and DS4 are detected by all three metrics while DS1, is not detected by any of the metric. The reduction in the frequency range adversely affects the performance of DI3 which is no longer able to detect DS1 damage. Although, the DS1, is indeed a small amount of damage at a considerable distance from the sensors. The performance of DI3 is still comparable to the RMSD index. In fact, the index corresponding to sensor 3 is expected to remain constant for the DS2, DS3 and DS4 scenarios, as the damage occurs outside the sensitivity zone of the sensor. But only DI3 shows stable values of the metric for sensor 3 while other three metrics do not show such stability. This stability in reality points towards the superiority of the $DI_3$ index.
trend of the metrics with increasing damage severity is obvious for all the metrics. This performance is similar to the study for the larger frequency range in the previous section.

For the aluminium plate, the figure 16 clearly shows that there is no increasing trend with the increase in the hole diameter for the RMSD, $DI_1$ and $DI_2$, on the other hand the $DI_3$ shows clear increasing trend. This behaviour too is in agreement with the results in the previous section.

The result for the CFRP beam for a smaller frequency range are similar to that in the previous section. All the methods, show an increasing trend with the increase in the size of delamination as seen in figure 17. It can be seen that the difference in the value for the RMSD technique is very small for Dam1 and Dam2 for sensor1 and Dam2 and Dam3 for sensor2 which is not desirable. The other 3 metrics show evenly increasing trend with significant differences in the values for different scenarios.

5.2. Analytical study

It was seen in section 4 that the $DI_3$ was robust even when the conductance spectra undergoes an amplitude shift. In order to better understand the performance of the indices, sensitivity studies were carried out on an analytical signal where controlled changes were introduced in the measured signal and the influence of these changes on the indices were studied. A point to note is that although the perturbations introduced were analytical, efforts were made to keep the changes physically equivalent to changes observed by the authors in their past work on real structures. The simulated cases (Sc) were:

- Sc1 baseline spectra
- Sc2 remeasured baseline spectra for threshold determination
- Sc3 appearance of additional peak in the spectra- (equivalent to damage)
- Sc4 scaling of spectra- (equivalent to change in the voltage exciting the piezo sensor)
- Sc5 scaling of spectra with additional peak
- Sc6 shift along frequency axis (horizontal shift) in the spectra
- Sc7 horizontal shift with additional peak
- Sc8 horizontal shift with small scaling of the signal (equivalent to change in temperature)

The spectra of the analytical signal is shown in figure 18. The magnified view shows the additional peak and the changes made. The horizontal shift introduced is based on extrapolation for temperature change corresponding to 15 $^\circ$C for the frequency range under investigation as reported in [32]. The magnitude of the signal for the temperature effect was reduced by a factor obtained from the work of Lim et al [33].
The four indices were then used for the simulated situations. The comparative plots are shown in figure 19. The scenarios marked in red are the one’s with simulated damage. So a large peak in red indicates positive damage detection. The bar for Sc2 is taken as threshold as it corresponds to the uncertainty in measurements for the same condition at different time instance. As can be seen, the RMSD shows positive detection for Sc3, Sc5 and Sc7 as is expected. But it also shows false detection for Sc4, Sc6 and Sc8. The indices DI1 and DI2 have similar performance. They show correct detection for the damage scenarios but also show false detection for Sc6 and Sc8. The index DI3 gives true positive for Sc3, Sc5 and Sc7 and gives true negative for Sc2, Sc4, Sc6 and Sc8. This analytical study gives the superior performance of the DI3 index as compared to the other indices. The superior performance for case with vertical shift was already provided in figure 11. It should be noted, that the authors in no way claim that the DI3 is insensitive to temperature induced changes. The DI3 is robust under the changing temperature conditions. Although DI1 may not be able to detect damage under large temperature changes seen in some applications, but it can easily overcome the changes in temperature which may be experienced inside a laboratory without controlled temperature over the course of the experiments. In case the changes in temperature are higher, appropriate temperature compensation techniques as covered by several other researchers [34–36] may need to be applied.

6. Conclusions

The paper proposes a new technique for improving the robustness of statistical comparison between the impedance signature of structures. The method makes use of the NCP to obtain a monotonically increasing function which can be used to statistically compare the two curves. Being monotonically increasing, several different statistical indices may be used for quantification of the difference between the power curves. These statistical indices are more robust and hence a better reflection of the condition of the structure. Three new indices are then computed based on the NCP. The metric based on the area under the curve and the RMSD between the NCP curves are based on the amplitude of the NCP measurements. As a result they show very similar behaviour under the various validation scenarios employed. The Frechet based index compares the shape of the curves. This index is shown to outperform the other two indices as well as the RMSD metric under the analytical and experimental tests performed. The experimental validation covers four different structures including composite and aluminium structures. It also shows the utility of the method for detecting the severity of the damage. The index based on Frechet distance shows correct detection and isolation as compared to the RMSD metric and hence is recommended to be used as a damage indicator. The sensitivity studies for a different frequency range for all the four structures have been presented as well. It can be seen that for changing the frequency band of interest, change the values of the metrics change but the overall behaviour is comparable. The decision to present results over a wide frequency range is better as often the frequency band sensitive to damage is not apriori known. In such cases, the possibility of robust health assessment on a large frequency band is more desirable and as such is a desirable feature of the proposed method.

Some analytical studies too were carried out to show the robustness of the metric. It is seen that the DI1 metric is insensitive to changes in the amplitude of the conductance signature, the horizontal shift while it accurately detects additional peak.

It should be noted that the calculation of the DI3 metric needs a rescaling of the frequency as well as the amplitude curves to a scale of [0,1]. As a result the relative values of the metric for different frequency ranges and materials cannot be compared. This is seen as a minor drawback of the method.

So the future aims will be to develop rescaling techniques to make the metric more objective and independent of the choice of frequency. The effectiveness of the index should also be investigated under changing temperature conditions before performing validation under in-service conditions. Another area for further investigation is the possibility of the use of the new metric for sensing sensor faults or malfunction. Special experiments will be designed as part of further work. Lastly, the comparison of the proposed DI1 metric will be undertaken with other metrics which too have superior performance as compared to the RMSD metric.

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