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A Baseline free approach to detect multiple damages in a beam type structure using response-only techniques

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Abstract

Structural health monitoring (SHM) is an important area that ensures the integrity and safety of all structures related to aviation, civil and mechanical engineering. Structural damage greatly affects the dynamic properties of a structure which, in turn, alters its measured dynamic response or vibrational characteristics. Hence, researchers have exploited this relation by devising damage detection techniques that are based on natural frequencies, mode shapes, mode shape curvatures, operational deflection shapes, operational curvature shapes etc. In most of these techniques, presence of damage is ensured with the change in the measured response. The measured response is typically in the form of Frequency Response Functions (FRFs) which requires the information of input data, usually the excitation force. In practice, it is difficult to measure the excitation force in operational areas and particularly, in randomly excited structures. So, in case of unknown excitations the response-only techniques are found useful, as they do not require input information and generate transmissibility functions (TFs) which contain information about damage. Furthermore, the majority of damage detection methods including the response-only techniques require the data of intact structures to distinguish the change due to damage, which in case of existing structures is impractical. To address this issue, smoothing techniques are applied on the available data to get presumed baseline information of undamaged structure. In this paper, two response-only techniques namely Operational deflection shape (ODS) FRF and Random Decrement (RanDec) are presented along with a smoothing technique to make the damage detection process baseline-free. To implement this modified approach in a beam-type structure, different damage scenarios are considered. The results of both response-only techniques are compared with those from FRFs and it is shown that RanDec technique gives better results when the record length of response and sampling time was increased.

Key Words: Baseline-free, damage index, FRF, ODS FRF, Random decrement technique, Response-only, Transmissibility function

1. Introduction

For appropriate maintenance, SHM systems continuously monitor the health of the structures and track the progressing structural damages. Long term operations, atmospheric conditions and environmental excitations may be the reason of the progression of these structural changes. Hence, all the infrastructures, whether civil, mechanical, or aerospace, impart a significant role in the economy of a country [1]. Therefore, it is pivotal to implement a damage identification method to observe the changes in the system and detect minor irregularities at an earlier stage to avoid any serious damage, which may result either in a life loss or economic disaster.

Damage or any structural change such as cracks, delaminations etc. directly affects the vibrational characteristics of the structure. Most of the damage detection methods frequently use these vibrational characteristics such as natural frequencies, mode shapes, modal curvatures etc. to detect the damage. Damage is quantified by the amount of changes induced in those parameters. The vibration-based methods are also classified as global damage diagnostic methods that provide the information of the whole structure [1, 2].

The most fundamental way of detecting damage is observing the changes in natural frequencies [3-5]. In normal conditions, damage can be detected confidently with 5% change in natural frequencies. However, this is not a strict criterion to detect the presence of damage because eminent changes in resonant frequencies, exceedingly 5%, have been observed in ambient conditions for both steel and concrete structures within a day. Besides detection, localization of damage is also required for repairing purposes. Variations in natural frequencies may not be enough to locate the structural damage, as multiple damage may cause same amount of change in frequencies. So, frequency variation-based methods are mostly applicable in simple structures to detect damage under constrained conditions due to its inherent limitations.

Mode shape analysis is more robust method for damage detection as compared to natural frequencies [6]. Since, damage alters the Eigen-parameters of a structure, it also affects the displacement mode shapes as they are associated with natural frequencies. The damage can also be quantified by the amount of changes induced in mode shape. These shapes are deflection pattern in a structure at natural frequencies, gives indication only for severe damage. However, the change due to damage is often lost in the presence of noise. In case of less severe damage, mode shapes retain their characteristic appearance and does not show any change in the behavior. The drawbacks associated with mode shapes analysis limit its use for further analyzing the dynamic parameters.

A further improvement was made by extracting mode shape curvatures from displacement mode shapes [5, 7, 8]. The second difference method is applied on mode shapes displacement to obtain the curvatures. Curvature mode shapes being quite sensitive to the structural damage, can be used as an efficient way to identify and localize the damage. However, measurement noise in mode shapes also get amplified from double differentiation, giving false information about the damage. To overcome this issue, mode shape curvatures require baseline information of the healthy structure as a reference. With no reference data, curvature mode shapes require substantial noise reduction process, hence making them unsuitable for detection of small damage and multiple damage cases.

By using strain mode curvatures, errors associated with double derivation can be avoided as they are extra sensitive to structural change and more tolerant to measurement errors as compared to conventional mode shapes [9-11]. However, modal strain energy method with no reference data can only detect severe reduction in thickness. To detect damage with low severity such as below 10% thickness reduction, data of intact structure are yet required.

In most of the vibration-based algorithms, changes in the measured response is used to check the presence of damage in the structure [12-15]. This measured response is typically in the form of frequency response function (FRF) which requires the information of input data, commonly the input force. However, in real case scenarios, it is often difficult to measure the accurate excitation force. The excitation data may not be easily available due to the fact that these unwanted excitations may come from multiple sources, i.e., from nature; earthquakes or wind buffeting, use of vibrating machinery; drilling, boring etc., external forces; such as traffic and human activities like jumping running, dancing [16,17]. The inability to measure these random vibrations demands for a strategy to eliminate the elemental use of input force from the damage detection algorithms.

For response-only techniques, the responses are collected at multiple points and one of these points is considered as reference [18]. These techniques process the responses and yield transmissibility functions (TFs) which contain the information of damage. There are many response-only techniques such as Operational deflection shapes (ODS) FRF, Random Decrement (RanDec) technique, power spectral density, Cepstrum method, Wavelet transform, Differential Quadrature Method (DQM) etc [19,20]. In this paper, ODS FRF (frequency domain modal identification method) and RanDec (time domain modal identification method) are presented due to the simplicity in the calculations of TFs. Efficacy of both methods are compared in this study with the directly extracted FRFs.

2. Proposed Methodology

2.1 ODS FRF Technique

ODS depict vibrational behavior (both components; resonant and forced) of a structure at each frequency, while mode shapes are defined only at resonant frequencies which may lack important structural information present at other frequencies [21]. FRFs are simply the transfer function between output and input which is a ratio between cross power spectrum (between excitation and response) and the auto power spectrum (excitation). So, FRFs require two channel data acquisition which involves a response and an excitation signal. Here, measurement of excitation signal is eliminated by fixing a response as a reference response, generating a TF [22]. It can be explained through a flow chart in Fig.1.

2.2 RanDec Technique

This technique is based on a simple averaging process of time segments of the measured response provided with an initial or triggering condition [23-25]. Proposed methodology has been demonstrated in the flow chart in Fig.2. To compute TFs, fast Fourier transform (FFT) of the cross and auto RanDec functions is taken to estimate spectral densities. Like ODS FRF, excitation signal is also replaced by the fixed response as a reference to create TFs.

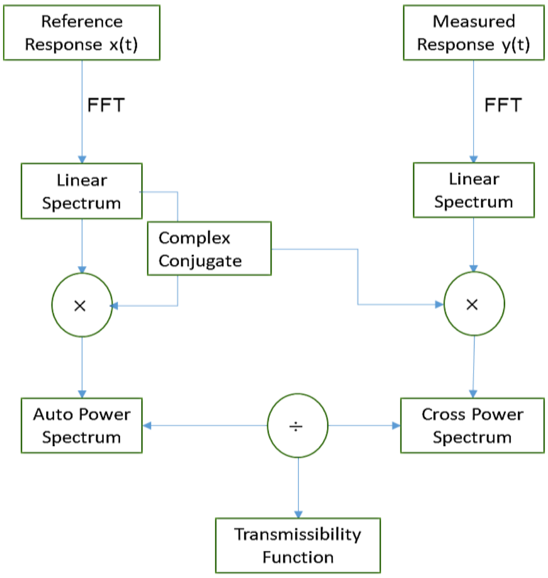

Fig. 1: Schematic Flow Chart for ODS FRF

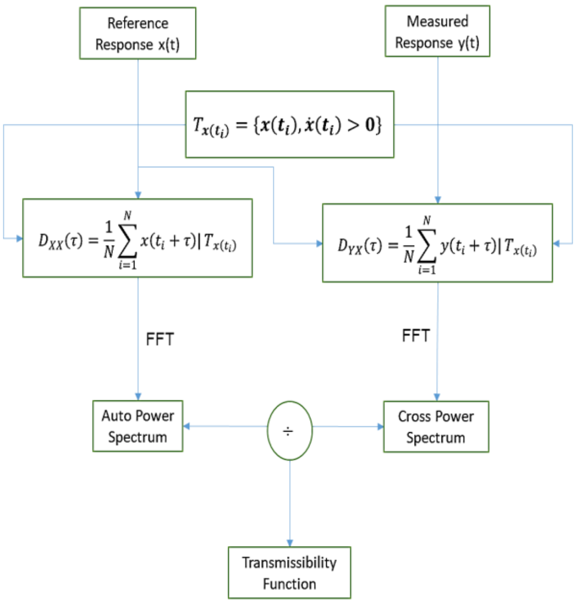

Fig. 2: Schematic Flow chart of Random Decrement Technique

TFs computed by both techniques, are complex in nature. After acquiring these TFs, their curvatures τ are estimated by using the central difference computation as in Eq.1.

$$\tau(u_0) = \frac{u_{-1} - 2u_0 + u_1}{(\Delta s)^2} \tag{1}$$

Where, u refers to the TF displacements at each measurement location and Δs is the spacing between these locations. To generate the damage indices that can indicate the damage locations without using any reference data, a smoothing polynomial is fitted on the curvatures of measured transmissibility functions [26]. For one dimensional structure such as beam, TFs can be fitted as

$$\tau_{fitted}(u) = \sum_{k=0}^{n} p_k u^k \tag{2}$$

Where, k is the order of the polynomial, and p_k refers to the coefficients calculated by the curve-fitting. For cubic polynomial fit, these coefficients are: $p_0 \to \tau_{i-2}, p_1 \to \tau, p_2 \to \tau_{i+1}, p_3 \to \tau_{i+2}$. The fitted and measured curvatures are shown in Fig.3.

The curvatures of the TFs are indexed for a specified frequency range, which is around first resonance as shown in Fig.4. This is because damage detection becomes less significant due to the difficulty in obtaining accurate data at higher resonances [27]. The damage index is obtained by computing the squared difference between the normalized measured TF-curvatures and fitted TF-curvatures of damaged structure [28]. Eq.3 represents the damage index

$$D(u) = \tau_{fitted}(u) - \tau_{measured}(u))^2 \tag{3}$$

The damage index values across the selected frequency range for all test points are then summed up to localize the damage. The proposed methodology is detailed in Fig.5.

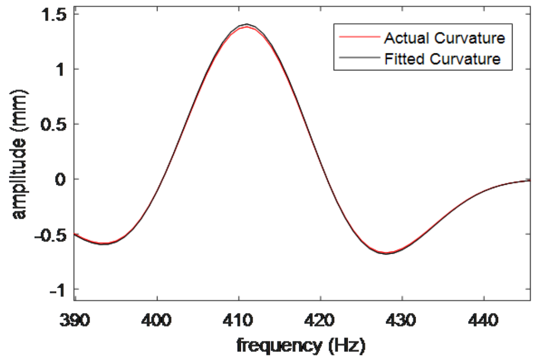

Fig. 3: Fitted & measured curvatures

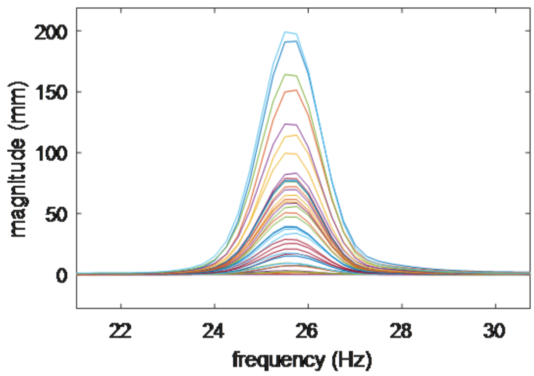

Fig. 4: Frequency range of 1st Resonance

3. Experimental Setup

The experiment was performed on an elastically suspended free-free steel beam (1000 × 20 × 50 mm). Damage scenarios include single and multiple damages with severity level as low as 2.5% and as high as 50% reduction in thickness. These damages were created as slots having width of approximately 0.4mm. There were 41 measurement points equally spaced along the beam length. To randomly excite the beam, an electromagnetic shaker was set at point 1 at the far left-end of the beam. A force transducer was used to record the input excitation force while, two accelerometers were used to measure the responses of the beam. Among these two accelerometers, one was fixed at the far right-end of the beam at point 41, while the other was used to measure responses at each 41 points along the length of the beam. The real and imaginary parts of the FRFs were directly extracted using FFT analyzer which was set on 1.6 kHz frequency span giving 0.25 Hz frequency resolution. For the single and double damage cases with 25% and 50% severity, the record length was 0.64 sec with 156.25µ sec sampling time. Whereas, for the cases of double damage with severity 2.5% and 5%, the record length was 4 sec with 244.14µ sec sampling time. To compensate the noise in the time response, linear averaging was done 10 times at each response point. The schematic of experimental setup is presented in Fig.6.

Time histories recorded from accelerometers were processed to calculate TFs in Matlab. Fig. 7 shows a comparison chart between time responses of the moving and fixed/reference accelerometers. It also illustrates the TFs derived from ODS FRF and RanDec incorporating the time response at point 3 near the left end of the beam.

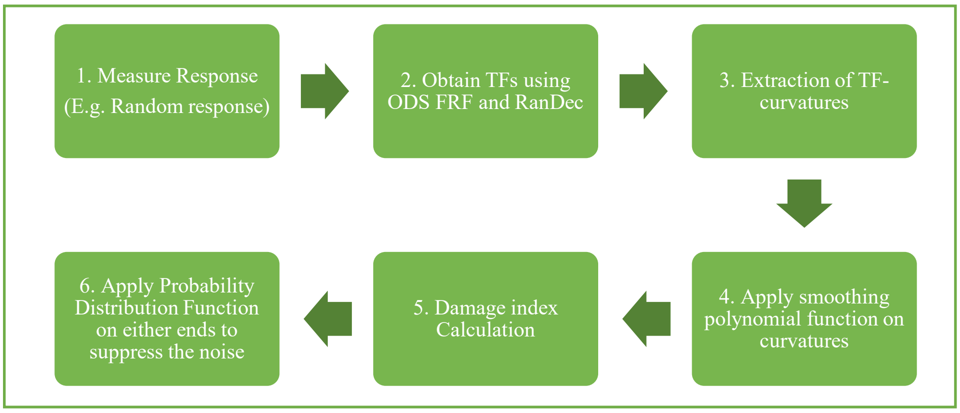

Fig. 5: Proposed methodology for response-only damage detection

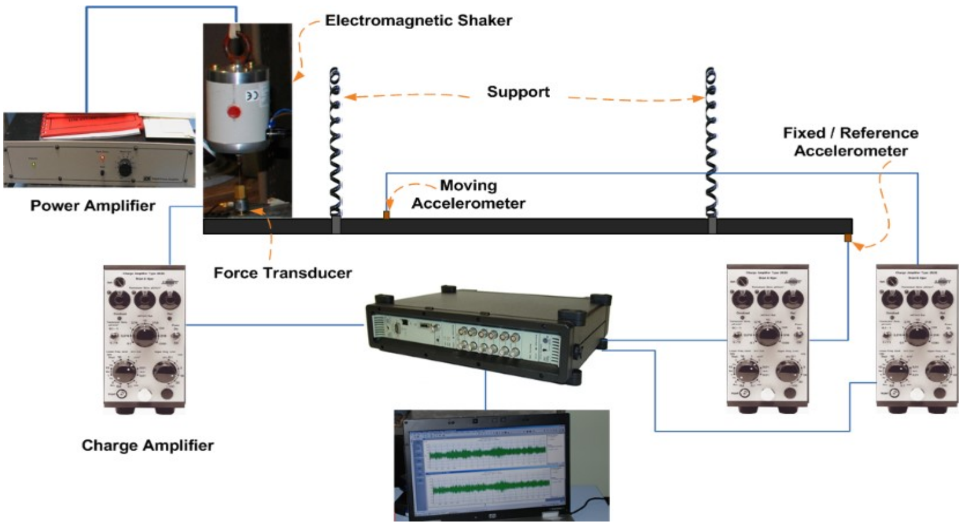

Fig. 6: Schematic diagram of the experimental setup

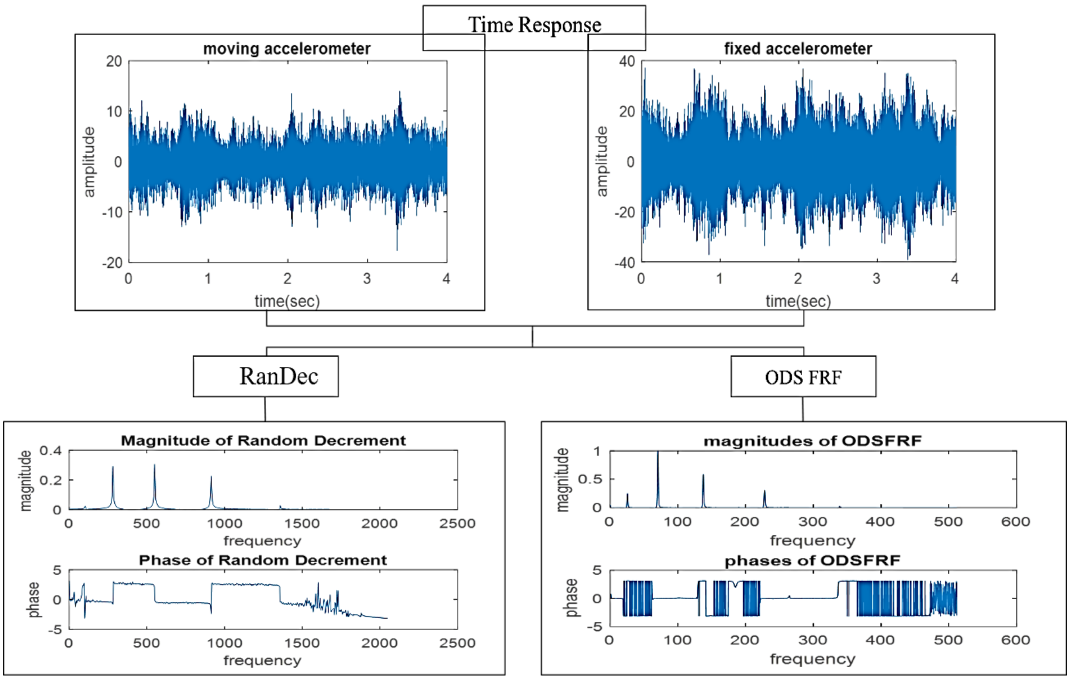

Fig. 7: FRFs comparison of ODS FRF and RanDec at Point 3

4. Results

For the damage cases considered here, the responses were measured as mentioned in section 3. Using the proposed methodology, damage indices were calculated for a range of frequency near 1st resonance for each case. All the results are shown in Figs. 8-12, in which the red dashed-dotted line indicates the location of damage along unit normalized beam length.

For the severe single damage case, both ODS FRF and RanDec methods were able to locate the damage. However, RanDec showed several side peaks indicating false possibility of damage as shown in Fig.8. For the case of severe double damage, only one damage can be detected using both techniques. ODS FRF provide damage indices with a single false peak while, RanDec shows many false peaks too, as can be seen in Fig.9.

Same results were achieved for double damage with 25% severity as shown in Fig.10. In both these cases, only one damage is visible while the other is lost in noise. It is likely due to the sampling rate being greater than the width of the damage slot. As, recorded time history was short in length, comprised of only 0.64 seconds with 156.25µ sec sampling time. Moreover, the frequency resolution for these cases was also low which was 1.5625 Hz. To get better results, the response should be recorded for a longer period, at least to 4 sec. Also, if more than one accelerometer could be used to measure data at multiple points that might also help in improving the damage detection process.

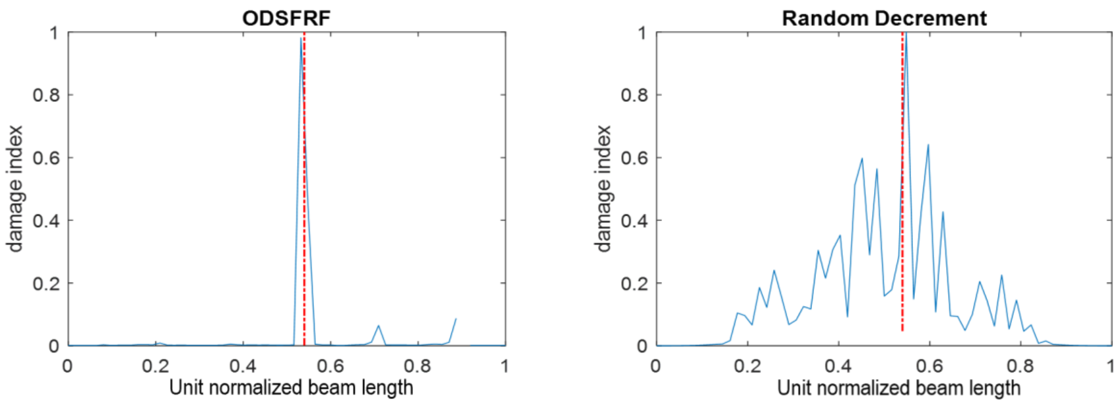

Fig. 8: Damage Case I—50% thickness reduction (single damage)

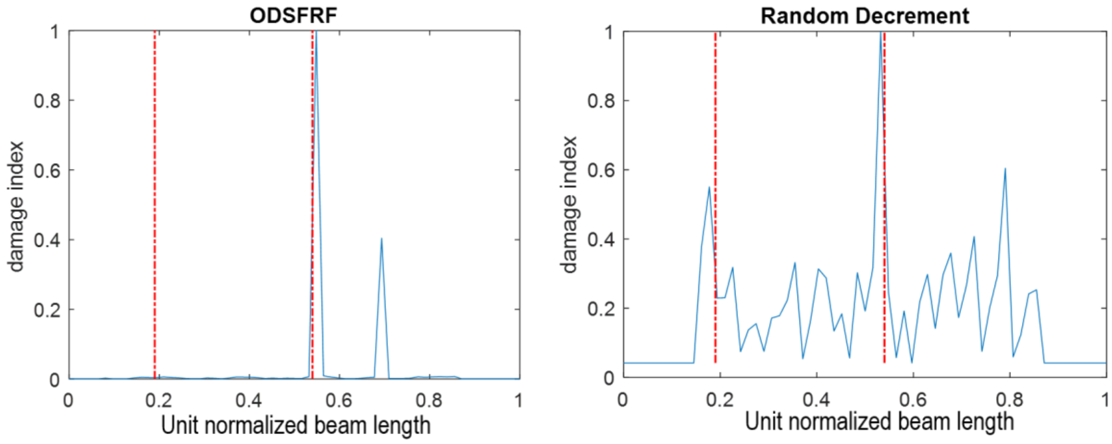

Fig. 9: Damage Case II—50% thickness reduction (double damage)

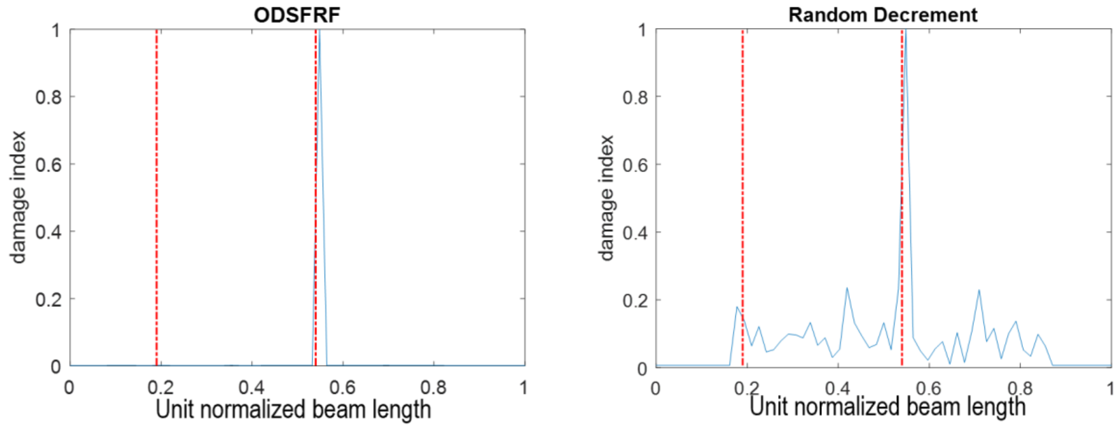

Fig. 10: Damage Case III—25% thickness reduction (double damage)

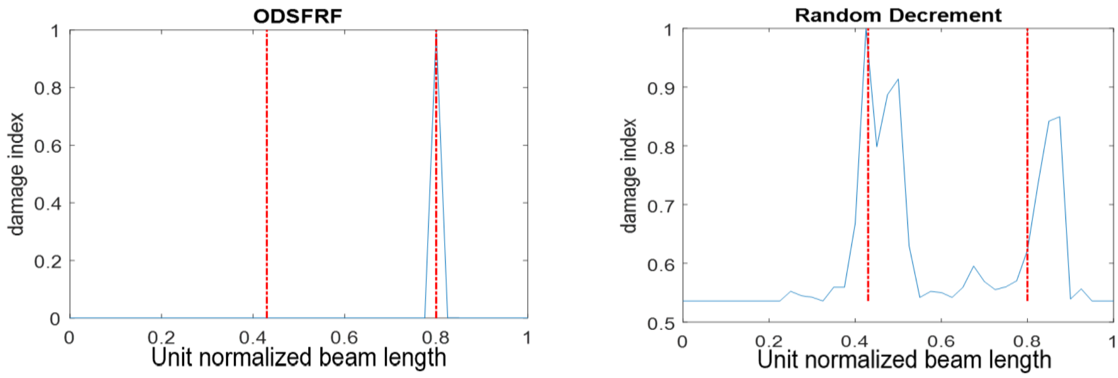

Fig. 11: Damage Case IV—5% thickness reduction (double damage)

Despite these short comings, it should be noted that these results were generated without using any baseline data and without the information of excitation force.

In case of double damage with 2.5% and 5% severity, the record length was increased to 4 sec with 244.14μ sec sampling time and frequency resolution of 0.125 Hz. For 5% severity, surprisingly RanDec showed better results by indicating both damage locations as can be seen in Fig.11. The peak for second damage was a bit shifted but its vicinity is clearly identified. Again, ODS FRF indicated the second damage with no other false peaks. For the very small damage with severity as low as 2.5%, ODS FRF indicated second damage while RanDec along with some side peaks clearly indicated both damage locations as can be seen in Fig.12.

From these results, it can be observed that by increasing the record length of time and improving the sampling time along with frequency resolution, RanDec provided better results by indicating vicinity of both less severe damages. These results can be further refined by using multiple accelerometers at different locations on the beam as well as by increasing the measurement points. ODS FRF on the other hand, indicated single damage even with short record length of time and with low frequency resolution. A comparison is also drawn between the results from these response-only techniques and the results by using FRFs. From Fig.13, it is observed that the results are not better even by employing the input force information. The damage indices generated by using FRFs were also able to locate a single damage in all cases. So, it can be concluded that with good resolution measured data, a baseline-free RanDec technique has the potential to be a successful damage detection technique for both single and multiple damage even with low severity.

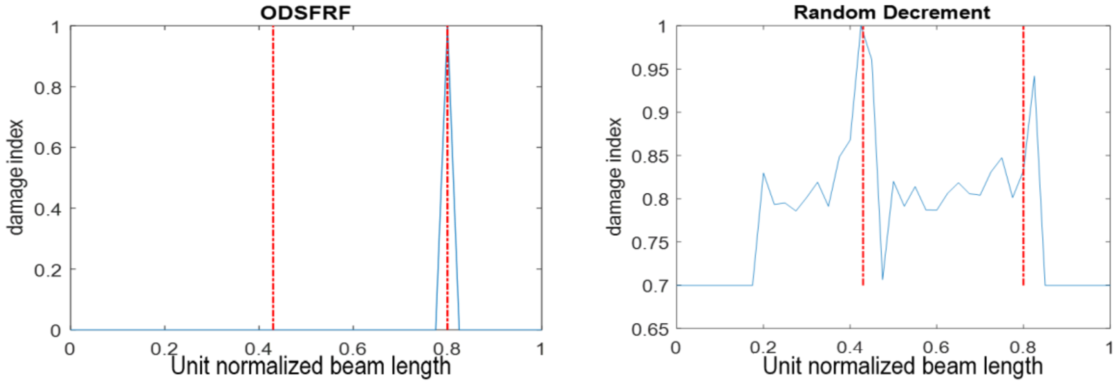

Fig. 12: Damage Case V—2.5% thickness reduction (double damage)

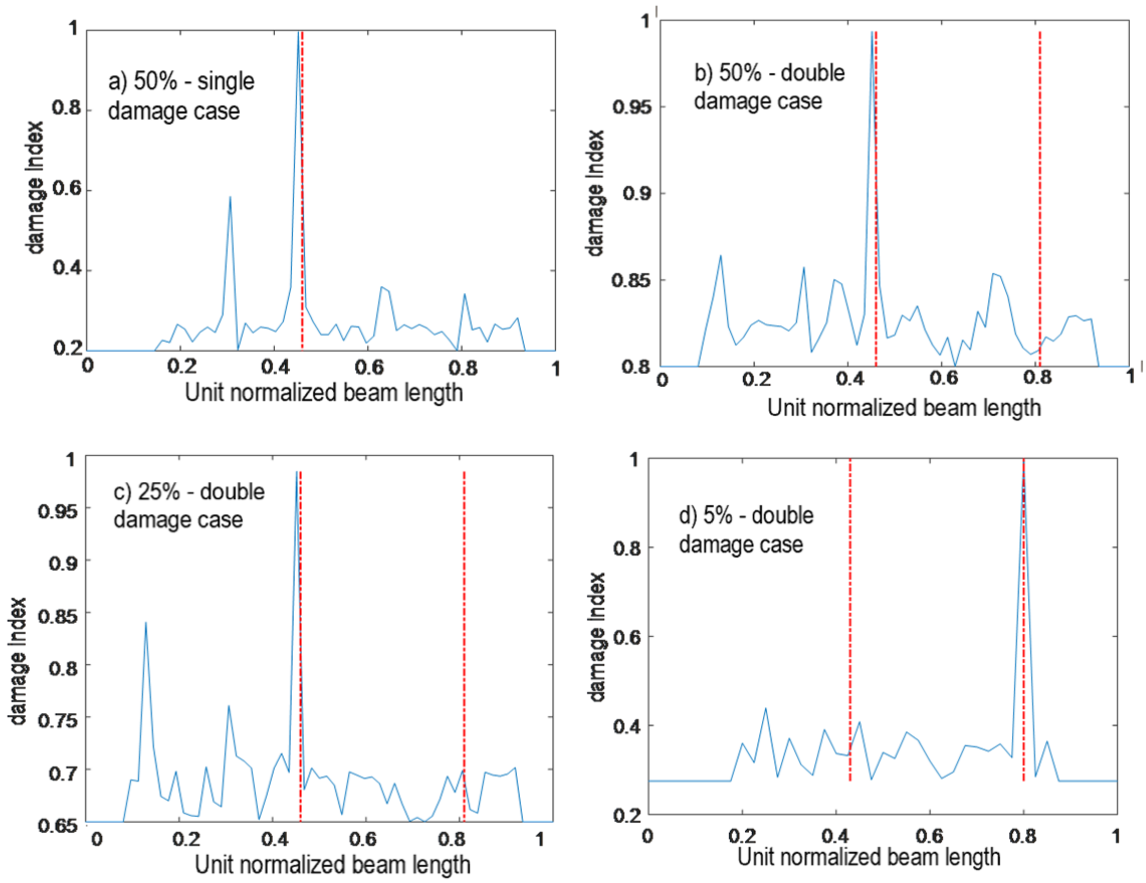

Fig. 13: Damage indices obtained from FRFs

5. Conclusion

This paper presented the use of baseline-free approach with response-only techniques for multiple damage detection in the beam type structure. ODS FRF & RanDec techniques were employed to generate TFs. While, a smoothing polynomial was used to create a reference data from the calculated TFs. This approach was implemented on beam type structure for five distinct damage scenarios including single and multiple damages with different severities such as 50% (single), 50% (double), 25% (double), 5% (double) and 2.5% (double). The damage severity is defined as the percentage reduction in beam's thickness. Both techniques were able to detect and localize one damage at a time accurately. However, when the record length of time was increased along with sampling time and frequency resolution, RanDec indicated the vicinities of both damage locations. Whereas, the results from ODS FRF were, although much refined than the results from RanDec but only indicating single damage. These results were computed by only using the response signals and only using the data from damaged beam. If the reference data are available, then the distinction can be further improved. These results were also compared with the results obtained from FRFs. It was noticed that with FRFs, only single damage was detected even for severe damage case. Hence, a baseline-free response-only RanDec method showed much better performance provided that the data is measured with good sampling time and frequency resolution. The results can be further refined by using multiple sensors at a time and by collecting data from more points along beam length.

6. References

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