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Damage detection in structures using frequency response functions ensemble with extended cosine based indicator

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Abstract. Although extensive investigations exist for structural damage detection, which often solely considers the stiffness reduction, or specific damage type like concrete spalling, this study aims to address a general novelty detection procedure for detecting the novelty, or so-called outlier from structural dynamic analysis with applying cosine based indicator in frequency response functions. This study also addresses a short review for the cosine indicator and modal assurance criterion, and their interrelation as well. The eight degree-of-freedom system is considered for the verification, and proves well performance in novelty detection.

1. Introduction

In-service structures undergo various forms of occasions that can affect their dynamic responses, such as temperature, bolt loosening, concrete spalling and so on. These changes in comparison with the initial structural state cannot be always considered as damages, but might be better called as novelty, or so-called outlier. The detection of these novelties makes structural health monitoring (SHM) of high significance, and also make it arduous since various factors can induce novelty. The accurate detection of damage rather than environmental change shall be afterwards challenging. In contrast to defining a damage-caused stiffness reduction, this study considers all response changes as novelty.

Over the past few years, various inspection techniques have been developed, such as vibration based, impedance based, probability based, and so on. The techniques can involve magnetic particle testing, acoustic testing, guided wave, new sensors like fiber bragg grating (FBG) and so on. For large-scale structures, vibration based techniques still occupy a large portion of applications due to their simple conduction, and effective work [1]. Vibration based techniques can be summarized into two categories: experimental modal analysis (EMA) and operational modal analysis (OMA) [2]. EMA usually applies to the structures in laboratory testing, and measures as much data as possible especially for the excitation and response, later to use frequency response functions (FRFs) and modal parameters such as modal damping, modal frequencies, mode shapes and their extensions like modal strain energy (MSE) in identifying the potential structural damages, or more generally, novelties. OMA behaves as an alternative for EMA by avoiding the measurement of excitation, and tries to achieve the same functions as EMA, which implies further applications for real engineering structures. For OMA, transmissibility,



as reference free technique, raised for decades ago, has been applied in several directions, such as damage detection [2-18], damage quantification [8, 10, 19], and so on. Review for transmissibility are available in [2, 10, 12].

Even alternatives can be found for novelty detection in terms of specific damage, like weight change can apply for spalling. It would be desirable to develop a strategy for general detection of novelty. This study tries to use extended cosine based indicator in the detection of novelty. Remaining work is organized as follows: section 2 gives the background of cosine indicator and its relation with modal assurance criterion (MAC) [19], and further applies in the FRFs to extract indicators for novelties; section 3 uses a eight degree-of-freedom system as verification, and section 4 addresses the concluding remarks.

2. Theoretical background

2.1. Cosine indicator and modal assurance criterion (MAC)

Cosine and MAC have been widely used separately, and recent advancement combined these two indicators, and addressed their kernel agreeing well, and detailed discussion can refer to [19]. For cosine indicator, which can be expressed as:

$$\cos(X, Y) = \frac{X^T Y}{|X||Y|} \quad (1)$$

where X, Y mean two vectors, $()^T$ means the transpose of $()$.

Then, MAC can be illustrated as:

$$MAC(X, Y) = \frac{(X^T Y)^2}{(X^T X)(Y^T Y)} = \left(\frac{X^T Y}{|X||Y|} \right)^2 = (\cos(X, Y))^2 \quad (2)$$

This relation unveils the interrelation between cosine indicator and MAC, and also explains why MAC can be applied as an objective function [19].

2.2. Frequency response functions

For a single loaded linear elastic structural system, the damped vibration can be illustrated with the second order differential equation:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \quad (3)$$

where M, C, and K denote the mass, damping, and stiffness matrices of the structure, respectively. $f(t)$ represents all the possible time dependent loading. $x(t)$ means the responses of the structure.

Then, the FRF can also be expressed as:

$$H_{(i,r)} = \frac{X_i}{F_r} \quad (4)$$

where X_i , and F_r refer to the frequency spectrum of response x_i and excitation f_r . FRF can also be expressed as the accumulation of discrete modes,

$$H_{(i,r)}(\omega) = \sum_{p=1}^n \frac{\phi_p^i \phi_p^r}{k_p - \omega^2 m_p + j\omega c_p} \quad (5)$$

where p denotes the p^{th} mode, n means the number of modes considered. k_p , m_p and c_p mean modal stiffness, mass and damping, respectively. From this equation, it is possible to see that the modal

parameters are hidden in the FRFs, and therefore possible to extract these modal parameters from FRFs through some algorithms, like expectation maximum algorithm.

2.3. Novelty indicator

From the discussion above, novelty indicators can be defined as the extension of cosine indicator [19],

$$CI = \left(\cos(FRF^u, FRF^d) \right)^Q \quad (6)$$

where $()^u$, $()^d$ denote the value under undamaged and damaged states, respectively. This cosine extension indicator has also been applied in transmissibility for damage detection [19], and it proves to be effective in detecting damages, and can measure the relative damage.

3. Experimental verification

An eight degree-of-freedom system shown in Figure 1 [20] is taken into consideration for unveiling the feasibility of the proposed approach in detecting the novelty. Detailed information for this experiment can be found in [16]. Bolts, springs, translating masses form the system. Different types of damage are simulated, linear and non-linear. Excitation of the system is driven by the voltage supplied. In this study, only the 14% damage at location 5 is considered, and the excitation is random, and changing voltage with 3V, 4V, 5V and 6V. Each response is recorded with an average of 40 measurements, and hanning window is used [20]. Further information about this experimental data analysis can also refer to [21].

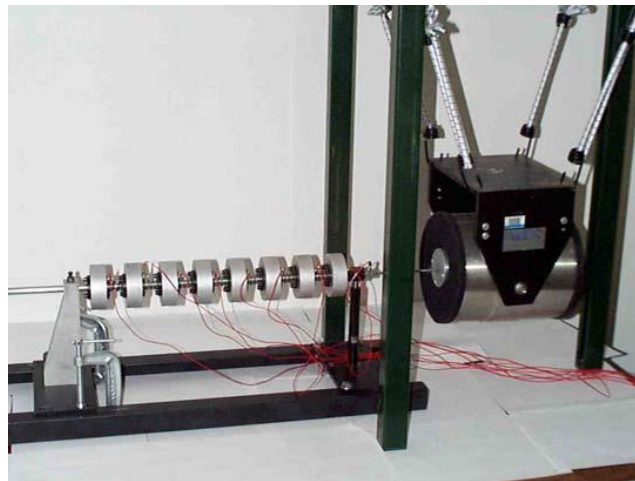


Figure 1. Experimental setup.

4. Results analysis

Results are computed and discussed in this section as follows in order to draw out the feasibility of the proposed novelty detection procedure. Figure 2 demonstrates the FRF (9, 2) for the structural system with and without damage under 6V excitation, and one can clearly find the natural frequency shift leftward, which implies the stiffness decrease. Certainly herein, it is possible to use the frequency change to estimate the stiffness reduction, since the change in the stiffness matrix leads to a corresponding change in the eigenvalue.

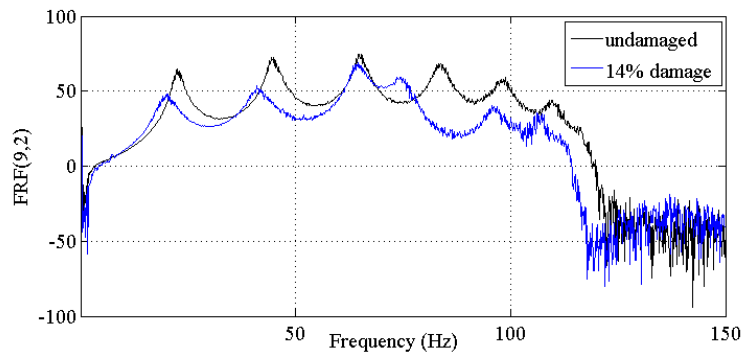


Figure 2. FRF(9, 2) for the structure with and without damage under 6V excitation.

Figure 3 shows the FRF (9, 2) for the structure without damage under 6V, 5V, 4V, and 3V excitation. From this figure, clear differences exist between these FRFs in the light of different voltage excitation. Similar phenomenon can be found in Figure 4 for the case with 14% damage. In theory, FRFs should be stable without change in the existing damage and nonlinearity. Herein, these difference can attribute to small nonlinearities, operational errors, or systematic errors. In general, these factors are all summarized as novelty in this study. Further investigation is indispensable in unveiling the kernel.

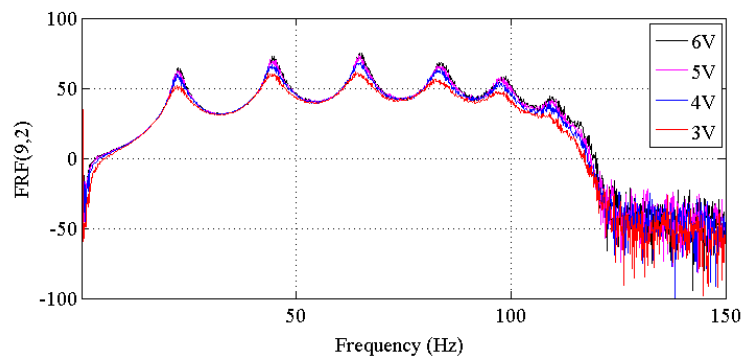


Figure 3. FRF(9, 2) for the structure without damage under 6V, 5V, 4V, and 3V excitation.

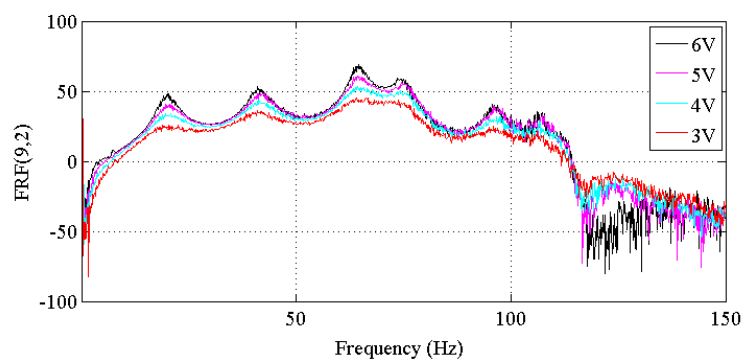


Figure 4. FRF(9, 2) for the structure with damage under 6V, 5V, 4V, and 3V excitation.

Figures 5, 6, and 7 demonstrate the CI (Q=1), CI (Q=2), and CI (Q=4) for undamaged and damaged scenarios, under 6V, 5V, 4V and 3V excitation. All novelties are successfully detected, like damaged scenarios for these three CIs, and as Q increases from 1 to 2, and 4, the CI performances become better as the difference of CI between undamaged and damaged scenarios increases. For the novelty induced between different voltage excitations, as the excitation voltage decreases from 6V, 5V, 4V, to 3V, the CIs increase. For different FRFs, the CIs show small variations without changing the general trend.

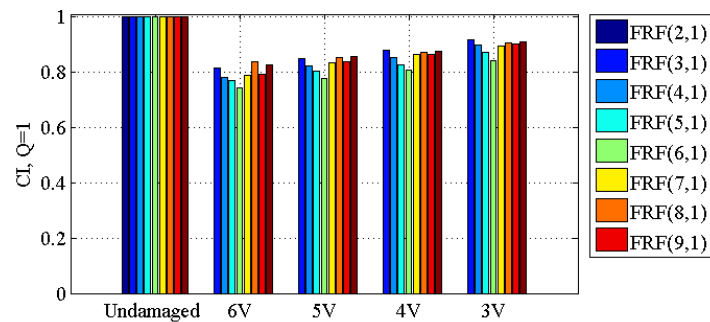


Figure 5. CI (Q=1) for the structure for undamaged and damaged, under 6V, 5V, 4V, and 3V excitation.

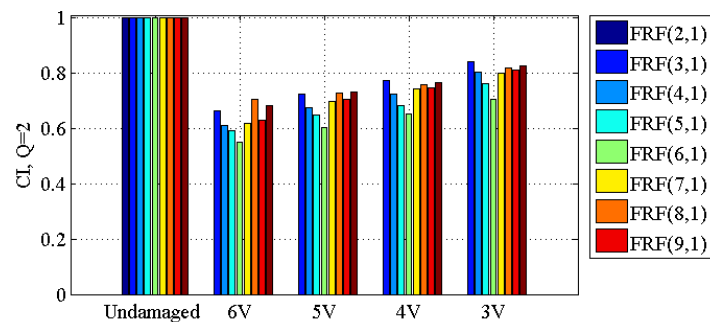


Figure 6. CI (Q=2) for the structure for undamaged and damaged, under 6V, 5V, 4V, and 3V excitation.

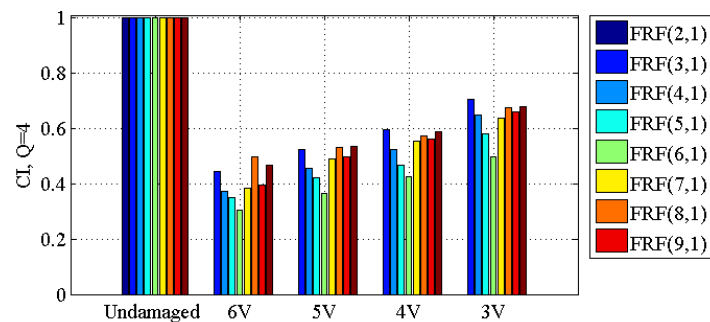


Figure 7. CI (Q=4) for the structure for undamaged and damaged, under 6V, 5V, 4V, and 3V excitation.

5. Conclusions

This study applies the cosine extended indicator in FRFs for detecting the novelties. Compared with an experimental investigation on an eight degree-of-freedom structure, this study demonstrates that the proposed novelty detection procedure performs well in identifying the novelties, regardless of the type of damages. The sensitivity of CI depends on the Q, which relies heavily on the engineering experience.

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ReferenceUncategorized References

- [1] Sohn H, Farrar CR, Hemez FM, Shunk DD, Stinemates SW, Nadler BR and Czarnecki JJ 2004 *Technical Report LA-13976-MS* Los Alamos National Laboratory
- [2] Zhou Y-L, Maia NMM and Wahab MA 2016 *Journal of Vibration and Control* (In press)
- [3] Zhou YL, Perera R and Sevillano E 2012 *Proceedings of the 6th European Workshop on Structural Health Monitoring* Dresden, Germany, July 2012
- [4] Zhou YL and Perera R 2013 *Proceedings of the 5th European-American Workshop on Reliability of NDE* Berlin, Germany, October 2013
- [5] Zhou YL, Figueiredo E, Maia N, Sampaio R and Perera R 2014 *Proceedings of International Conference on Noise and Vibration Engineering (Isma2014) and International Conference on Uncertainty in Structural Dynamics (Usd2014)* 527-535
- [6] Zhou YL and Perera R 2014 *Proceedings of the 9th European Conference on Structural Dynamics (EURODYN 2014)* Oporto, Portugal, June 2014
- [7] Zhou YL, Figueiredo E, Maia N, Sampaio R and Perera R 2015 *Structural Control & Health Monitoring* **22**(10) 1209-1222
- [8] Zhou Y-L, Figueiredo E, Maia NMM and Perera R 2015 *Shock and Vibration* **2015**(Article ID 290714)
- [9] Zhou Y-L, Wahab MA and Perera R 2015 *International Journal of Fracture Fatigue and Wear* **3** 254-259
- [10] Zhou YL 2015 *PhD thesis*
- [11] Zhou Y-L and Wahab MA 2016 *Journal of Vibroengineering* **18**(7) 4491-4499
- [12] Zhou Y-L, Maia NMM, Sampaio R and Wahab MA 2016 *Structural health monitoring - An International Journal* (In press)
- [13] Zhou Y-L, Maia NMM, Sampaio R, Qian XD and Wahab MA 2016 *Proceedings of the 2016 Leuven Conference on Noise and Vibration Engineering (ISMA 2016)* **Leuven, Belgium, September 2016.**
- [14] Zhou Y-L, Yang XB and Wahab MA 2016 *International Journal of Fracture Fatigue and Wear* **4** 200-203
- [15] Khatir S, Belaidi I, Serra R, Abdel Wahab M and Khatir T 2016 *Journal of Vibroengineering* **18**(1) 202-213
- [16] Khatir A, Tehami M, Khatir S and Abdel Wahab M 2016 *Journal of Vibroengineering* **18**(8) 5063-5073
- [17] Gillich G-R, Praisach Z-I, Abdel Wahab M, Gillich N, Mituletu IC and Nitescu C 2016 *Shock and Vibration* **2016**(Article ID 2086274) 10 pages; <http://dx.doi.org/10.1155/2016/2086274>
- [18] Khatir S, Belaidi I, Serra R, Abdel Wahab M and Khatir T 2015 *Mechanika* **21**(6) 472-479
- [19] Zhou Y-L and Wahab MA 2017 *Engineering Structures* **2017**(141) 175-183
- [20] <http://www.lanl.gov/projects/national-security-education-center/engineering/ei-software-download/thanks.php>
- [21] Worden K, Allen DW, Sohn H, Stinemates DW and Farrar CR 2002 *Los Alamos National Laboratory Report LA-13903-MS*