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DAMAGE DETECTION BY TRANSMISSIBILITY CONCEPTION IN BEAM-LIKE STRUCTURES

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Abstract: Even though lots of methods for detecting damage have been developed, early and global output-based damage detection still have difficulty. In this study, a global indicator is constructed for detecting the structural damage from a global aspect. And a simulated clamped-clamped steel beam is analyzed to check the applicability of the proposed approach. The results show the well performance of the proposed approach, and further investigation of experiment validation will be conducted.

Keywords: Transmissibility; Damage detection; Structural health monitoring

1 INTRODUCTION

Structural health monitoring (SHM) has become a global trend since the damage problems in big structures like oil pipes, tall buildings and so on attracted a lot of attention from engineering field and research field as well. The damage detection problems in real engineering put forward the research in scientific field. However, in the beginning, damage detection is based on the measurement of real structures or experimented models. For the purpose of saving cost, numerical analysis has been raised and processed a booming development in the past decades for almost all engineering fields, for instance, joint analysis, crack propagation [1-2], and it has also been widely used in SHM, for instance, in [3], single side damage is simulated with three different finite element models – solid, shell, and beam model, and the beam modal analysis is conducted entirely with numerical analysis.

In SHM, lots of different methods have been developed, from measurement aspect, oil penetrating based, magnetic based, impedance based, vibration based, ultrasonic, acoustic emission, and so on. With the development of high technology, X-ray, acoustic emission and other high technology integrated instruments like optical fibre have also been introduced to SHM.

On the other hand, data analysis is another aspect, a large quantity of algorithms have also been developed like curve fitting, Poly-Max, Rational fractional Polynomial (RFP) and so on.

However, the aforementioned algorithms are based on the excitation and response; and this restricted the application in large civil infrastructures like long-span bridges. Then, researchers tend to find some output based methods for SHM. Transmissibility is one of the pursuit results in this period.

Transmissibility, due to its own characteristic depending on output data only [4, 5], gives the possibility in a better use in real engineering. And it has been developed for damage detection [6, 9], localization [11], and quantification [7, 8], and response reconstruction [10], and so on. But difficulty still exists as damage can be caused by a lot of changes, and environmental varieties will also add more hardship in real engineering.

In this study, a new transmissibility based damage detection methodology is proposed with assuming that damage will change the structural stiffness, no matter the damage is caused by any form of damage. Later, transmissibility based damage detection procedure is constructed, and then a simulated beam is used for testing the proposed approach.

2 TRANSMISSIBILITY

Considering a linear multiple-degree-of-freedom system, the dynamic equilibrium equation can be written by the well-known second order differential equation:

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)=\mathbf{f}(t) \quad (1)$$

Where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices of the system, respectively, f(t) is the input force vector, x(t) contains the responses of each degree-of-freedom of the system.

Herein, for a harmonic applied force at a given coordinate, the transmissibility between point i and a reference point j can be defined as

$$T_{(i,j)}=\frac{X_i(\omega)}{X_i(\omega)} \quad (2)$$

where $X_i(\omega)$ and $X_j(\omega)$ are the complex amplitudes of the system responses $x_i(t)$ and $x_j(t)$, respectively, and ω is the frequency.

For calculating transmissibility, it might be calculated in some manners; amongst them to use the frequency response function (FRF) is one easy and convenient way in early damage detection analysis,

$$T_{(i,j)}=\frac{X_i(\omega)/F_t(\omega)}{X_j(\omega)/F_t(\omega)}=\frac{H_{it}(\omega)}{H_{jt}(\omega)} \quad (3)$$

where t is the excitation point, and H represents the FRF.

From Equation (3), one can see that transmissibility can be estimated by ratio of two FRFs, and since FRF change can be used for detecting damage, logically speaking, transmissibility change might also be used for detecting damage.

On the other hand, modal assurance criterion (MAC) might also be used to estimate the change of transmissibility before and after damage. Note that considering the imperfect of the response along the entire frequency domain, one might only choose one segment within the frequency band of interest. Then it might be expressed as:

$$MAC(T^d_{(i,j)},T^u_{(i,j)})=\frac{((T^d_{(i,j)})^T(T^d_{(i,j)}))^2}{((T^d_{(i,j)})^T(T^d_{(i,j)}))((T^u_{(i,j)})^T(T^u_{(i,j)}))} \quad (4)$$

where $T^d_{(i,j)}$ represents transmissibility under damaged condition, while $T^u_{(i,j)}$ means the transmissibility under intact condition, $()^T$ means transpose.

For Equation (4) above, threshold should be set to each equation, while this depends on the engineering experience of each user. Note that the threshold will directly determine the predicting results of the structural damages. In this study, the value under intact condition is set as threshold.

For detecting the structural damage, procedures can be set as follows:

Step 1: To extract the structural dynamic response, Fourier transform is used to analyze the data in frequency domain with deriving the transmissibility;

Step 2: To calculate the damage indicator with Equation (4);

Step 3: With the threshold set before, one might predict whether the structure is damaged or not.

3 NUMERICAL STUDY

For checking the feasibility of the aforementioned damage detection procedure, numerical analysis is carried out with a clamped-clamped steel beam shown in Fig. 1. And the physical properties are shown in Table 1. The beam is divided into 20 elements on average, and each element is named as shown in Fig. 1. Then the excitation is loaded at node nine (right boundary of element eight) with a unit impulse in frequency domain. And the beam is considered as Euler-Bernoulli beam with one dimension model. And a constant damping ratio of 0.2% is taken into account for simulating a slight damping.

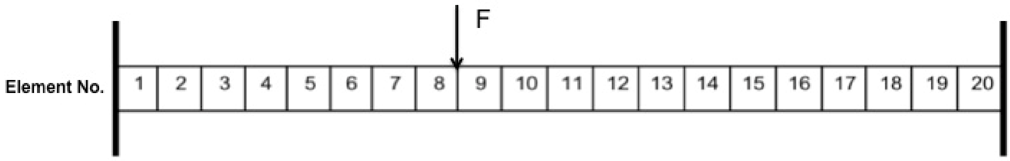

Fig. 1 Numerical simulation with 50 elements

Table 1 Beam properties

Beam properties	Value
Young's modulus (GPa)	210
Poison's ratio	0.3
Density (Kg/m^3)	7800
Length (m)	1.0
Width (m)	0.05
Thickness (m)	0.006

For examining the proposed damage detection procedure, various simulations are conducted and analysed by considering single damage in element three. Damage has been introduced with four levels, which are shown in Table 2.

Note that in this study herein presented, the damage is introduced by stiffness reduction into the distinct element, where only the element will be influenced, in an attempt to simulate the structural damage in real engineering. Then, the vertical acceleration response of each node was derived and analysed.

Table 2 Damage scenarios

Scenario	Value
D0	Intact state
D1	5% stiffness reduction
D2	15% stiffness reduction
D3	40% stiffness reduction

4 RESULTS AND DISCUSSION

In order to validate and illustrate the applicability of the proposed approach, the aforementioned damage detection procedure is conducted and the results are as follows:

Fig. 2 and Fig. 3 show transmissibility T(15, 4) and T(11, 3) under D1-D3 along with intact condition D0, respectively.

From the figures, one can find that:

(i) The difference between D1, D2, D3 and D0 is clear in the entire frequency domain, which suggests that the transmissibility might be used to detect the damage. This can be also found in Fig. 3.

(ii) The peaks and anti-peaks in Fig. 2 all move forward to the left part, this might suggest the structural resonant frequencies decrease as the damage enlarges. This can also be confirmed in Fig. 3 in part, however, one can find in Fig. 3 that one anti-peak does not move to the left part. This might be resulted from the chosen transmissibility.

Note that to choose a proper transmissibility for identifying structural damage is a key issue during the whole SHM process, while until now no exact rules have been drawn out, one need to choose according to his own experience.

To summarize, using the transmissibility change, if the transmissibility is well chosen, it can successfully detect structural damage.

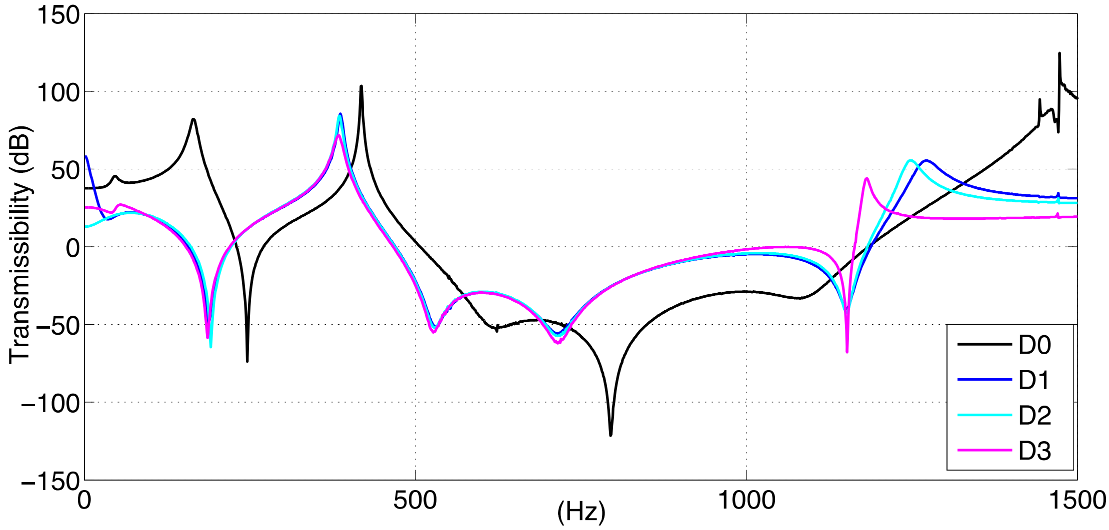

Fig. 2 Transmissibility T(15, 4) under D1-D3 along with D0.

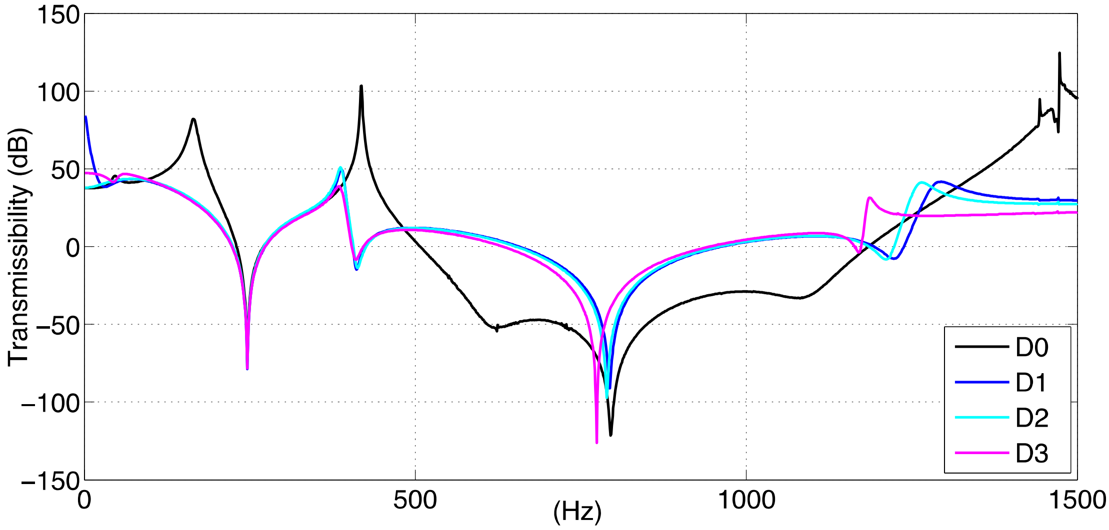

Fig. 3 Transmissibility T(11, 3) under D1-D3 along with D0.

Considering the MAC value defined in Equation (4), Table 3 shows the MAC calculated for each damage scenario.

From the Table 3, it can be found that:

(i) For all the cases, no matter how the frequency band is chosen, the MAC value can detect the damage, while if the frequency band is not well chosen, the difference might be little, like T(11,3) under frequency band [800, 1000] Hz.

(ii) If the entire frequency band is used, then even small damage occurs, the MAC value will decrease a lot.

(iii) In both T (15, 4), T (11, 3), if the entire frequency band is used, the MAC value did not change monotonically in accordance to the damage severity.

(iv) If the frequency band is well chosen, like T(15, 4) under [480, 500] Hz, T (11, 3) under [800, 1000] Hz, the MAC value can change monotonically in respect to the damage severity.

Table 3 MAC value of each damage scenario

Scenario	MAC value for T (15, 4)		MAC value for T (11, 3)	
	[0, 2048] (Hz)	[480, 500] (Hz)	[0, 2048] (Hz)	[800,1000] (Hz)
D0	1.0000	1.0000	1.0000	1.0000
D1	0.1604	0.9941	0.2349	0.9983
D2	0.1428	0.9934	0.3403	0.9980
D3	0.1471	0.9926	0.2751	0.9936

For better understanding the performance of MAC value, Fig. 4 and Fig. 5 show the comparison between T(15, 4), T(11, 3) under the entire frequency band, and under each own well fitting frequency band, respectively. Herein, note that the fitting frequency band is a critical issue to choose, while it will determine the performance of the MAC result.

From Fig. 4, it is clear that the MAC results did not hold a straight relation with the damage severity, while when damage happened, it changed a lot. And in Fig. 5, one can find that the MAC value decreased small as damage happened, however, one can find that the MAC value decreased monotonically in according to the damage severity. This suggests that if the frequency band is well chosen, the MAC value might used to assess the damage severity.

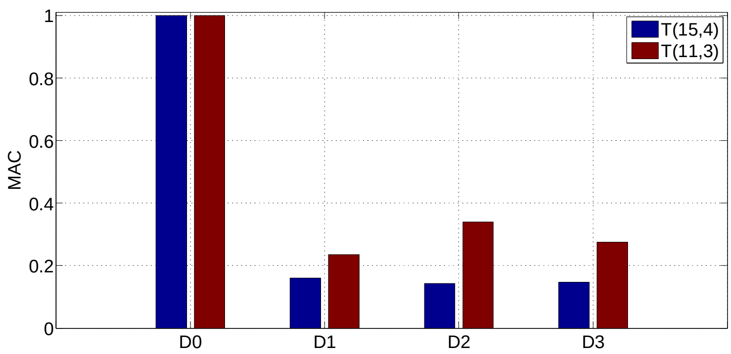

Fig. 4 MAC value of T(15,4), T(11, 3) under D1-D3 along with D0 with frequency band [0,2048] Hz.

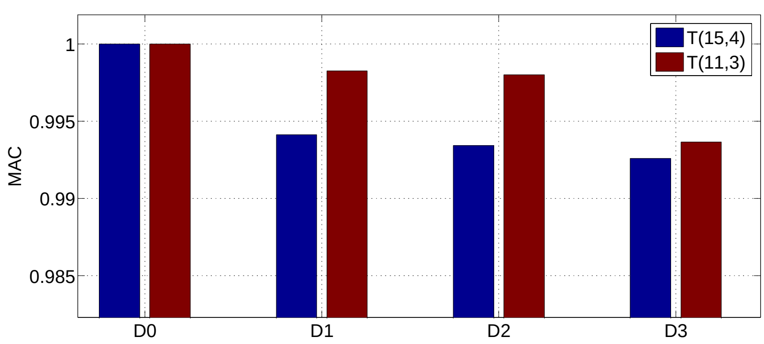

Fig. 5 MAC value of T(15,4) [480, 500] Hz, T(11, 3) [800, 1000] Hz under D1-D3 along with D0.

5 CONCLUSIONS

In this study, a new methodology for detecting damage in beam-like structures is proposed with a clear inference. Note that this proposed methodology is for Euler-Bernoulli beam-like structures. The numerical analysis results show the well performance in damage detecting, while if the frequency band is well chosen, it might also be used for assess the damage severity. Further investigation is needed in order to test the feasibility of the proposed methodology in noisy environmental experiment data.

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