Damage Detection of Beam Structure using Frequency Response Functions

R.Murali[1]
[1]*Assistant Professor,*
Department of Civil Engineering,
Kingston Engineering College, Vellore, Tamil Nadu, India-632 059.

Abstract:

The global dynamic behavior of structure can affect by the Presence of damage. Hence detection and quantification of damage has a greater significance in the context of structural health monitoring. This paper is based on frequency response function for detecting the presence and severity of damage in the structure. The variations in frequency response function is taken as a feature to detect damage. The different damage severities and the various damage locations change the amplitudes, shift peaks and alter shapes of the Frequency Response Functions (FRFs). The severity of the damage is quantified through severity index developed based on Frequency domain assurance criterion (FDAC).The major advantage of the proposed technique is that frequency response function can be measured easily through experiments. Numerical simulation studies have been carried out using a cantilever beam with varied damage cases. The damage is simulated through reduction in stiffness of a single or multiple element of finite element beam model considered. The investigation carried out in this paper clearly indicate that the technique based on FRF is effective for damage identification and quantification.

Keywords: *Frequency response functions (FRF), damage locations, frequency domain assurance criterion (FDAC)*

I. INTRODUCTION

Structural health monitoring (SHM) and damage detection has become an important issue in many fields such as civil, mechanical and aerospace engineering. In the past two decades, the issues related to structural health monitoring (SHM) and damage detection in civil, mechanical and aerospace engineering infrastructure have been paid considerable attention by the research community.

The goal of SHM is to determine and classify damages (location, type, and severity) for a dynamical system exposed to varying environmental and operational conditions as well as instrumentation noise (i.e., ‘real world’ conditions). Several books have been published recently dealing with SHM [Adams, 2007, Balageas et al. 2006, Giurgiutiu 2008, Glisic and Inaudi 2008,]. Although the field of SHM has experienced significantly increased research during the last decade, a damage detection method that can provide quantitative damage information anywhere in a complex structure, such as bridges, is still under development.

The basic principle of an SHM system is that damage alters stiffness, mass or damping of a structure and in turn causes a change in its dynamic response. The complete health state of a structure can be determined based on presence, location, type and severity of damage (diagnostics) and estimation of remaining useful life (prognostics).

In this paper, an algorithm based on Frequency Response Function (FRF) is presented. The algorithm is used to detect damage, severity of damage and monitor the increase in damage using the both input and output measured data. The method is applied to the numerical simulation studies on cantilever beam model.

II. FREQUENCY RESPONSE FUNCTION BASED DAMAGE DETECTION METHOD

Rupika P Bandara, Tommy HT Chan, David P Thambiratnam (2014) developed FRF-based damage identification approach for structural health monitoring.The proposed approach utilized artificial neural networks, frequency response functions and in order to reduce size of measured FRF data, the principal component analysis technique is adopted. The proposed method was applied for the three-story bookshelf structure.

Murali.R, Sankaran.S(2015) proposed a damage identification to determine the severities of damage in simply supported beam. The proposed technique based on the frequency response functions (FRF) and frequency domain assurance criterion (FDAC) for determining the damage.

I.C.Davis, A.L.Wicks(2002) proposed a damage identification to determine severities damage in six identical cylinders. The proposed approach utilized frequency response functions (FRF).

III. CONCEPT OF FREQUENCY RESPONSE FUNCTION

FRF can be derived directly from the force and response information. The excitation force can be random, sinusoidal, and periodic or impact. Theoretically, the FRF does not depend on the type of excitation as it is calculated from the ratio between the response and force.

Multiple force inputs can vibrate a structure with reasonably uniform amplitudes compared with vibration under a single input. Fig.1 shows a measurement set-up with shaker excitation.

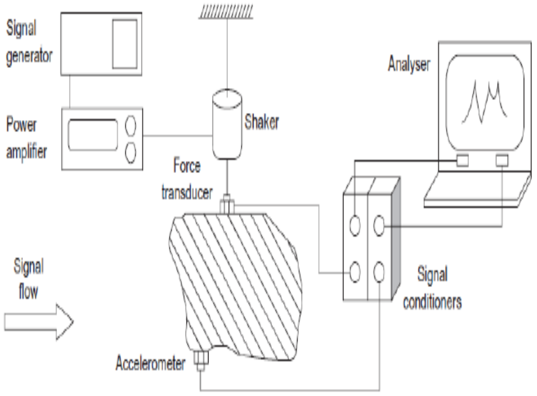

Fig.1Measurement Set-Up with Shaker Excitation

A typical measurement set-up in a laboratory environment has three constituent parts. The first part is responsible for generating the excitation force and applying it to the test structure and the second part is to measure the response data and the third part provides signal processing capacity to derive FRF data from the measured force and response data.

IV. ESTIMATION OF THE FRF

Estimation of the FRF simply involves exciting the structure with a measurable force, measuring the response and then calculating the ratio between the force and response spectra. For example, the input signal $f(\omega)$ with respect to frequency (ω) is the force applied to the structure and the output signal $x(\omega)$ is the response motion signal obtained from the accelerometers attached to the input after Fourier transformation, as shown in following equation,

$$H(\omega)=\frac{X(\omega)}{F(\omega)}=\frac{Output}{Input}$$

FRF can be presented in rectangular coordinates (frequency vs. real part, and frequency vs. imaginary part) or in polar coordinates (amplitude vs. frequency and phase vs. frequency).

V. PROPOSED METHOD

In this paper, a method has been developed to identify the presence of the damage as well as quantification of damage in terms of its severity.

The changes in the values of natural frequencies and FRF values has been used for the identification of the presence of the damage in the system.

The severity of the damage is identified through the newly proposed severity index. The severity index is developed based on Frequency response function correlation index called Frequency Domain Assurance Criterion (FDAC). FDAC can be simply defined as the correlation between FRF of the two states (reference-undamaged and damaged state). The Frequency Domain Assurance Criterion (FDAC) used in this paper is given by,

$$FDAC(\omega)=\frac{\left(\sum_{n=1}^{N}\{H_1(\omega,n)\}\{H_2^*(\omega,n)\}\right)\left(\sum_{n=1}^{N}\{H_2(\omega,n)\}\{H_1^*(\omega,n)\}\right)}{\left(\sum_{n=1}^{N}\{H_1(\omega,n)\}\{H_1^*(\omega,n)\}\right)\left(\sum_{n=1}^{N}\{H_2(\omega,n)\}\{H_2^*(\omega,n)\}\right)}$$

Where,

H1 = FRF data of undamaged structure
H2 = FRF data of damaged structure
N = total number of frequency points
*= complex conjugate
ω = frequency point

The FDAC value lies between 0 and 1.If the FDAC is equal to 1 it is shows perfect correlation and if it is equal to the 0 it is shows perfect non- correlation. Therefore the FDAC value will drop below unity for damaged structure. In order to identify the severity of damage in the structure, three levels of damage has been proposed and their corresponding FDAC values is shown in below Table.1

Table.1 Level of Damages

Severity Of Damage	FDAC Value
Low	0.95 to 1.0
Medium	0.75 to 0.95
High	0-0.75

The severity of the damage can be identified through severity index (SI) developed from FDAC. Severity index (SI) of the FDAC is equal to the average of drop values of FDAC for the selected frequency range of all sensors measured in the structure.

VI. NUMERICAL STUDIES

The cantilever beam model shown in Fig. 2, has been usedfor the demonstration of the efficiency of the proposed FRF based damage detection technique.

The span of the beam is 20.0m and the cross sectional dimension is 0.25 X0.5 m. The beam is modeled using 20 beam elements(3 degrees of freedom per node).

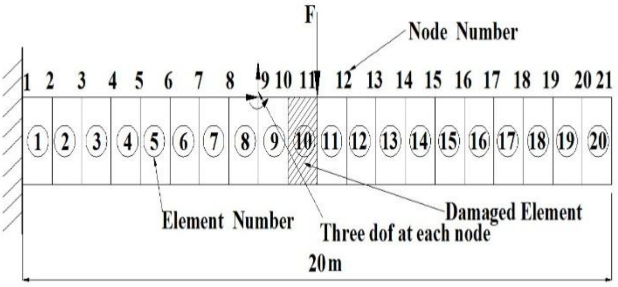

Fig .2 Cantilever Beam

The material properties of the beam are: Young's Modulus, E = 2.1E11Pascal's; Mass density, ρ= 7800 Kg/m^3.
The time history responses are computed using New mark's (constant average acceleration) time integration scheme. The chosen sampling frequency is 5000Hz.

The damage is simulated into simulated beam by reducing the stiffness of various elements by varied percentages. The various damage cases considered has been tabulated as follows.

Table. 2 Three Different Damage Cases Induced In Cantilever Beam

Case No.	Damage Element Number	Percentage Of Damage
1	10	20%
	10	60%
2	15	20%
	15	60%
3	4	20%
	9	50%
	16	70%

The first natural frequencies of the undamaged beam and damaged beam of the various cases considered is given in Table 3. It can be clearly observed from the table that there is decrease in natural frequencies for the damaged state for all cases when compared to the reference undamaged state. We can also observe that the amount of shift is directly proportional to the severity of the damage in the beam.

Table. 3 First Natural Frequencies for Various Damaged Cases

% dam	Natural frequencies in Hz			
	undam	Case(1)	Case(2)	Case(3)
20%	2.87	2.83	2.80	2.64
60%	2.87	2.42	2.62	2.44

The frequency response function of the beam corresponding to11th, 16th node and multiple damage case with multiple locations considered are plotted along with the undamaged state FRF in Fig 3, 4 and 5.

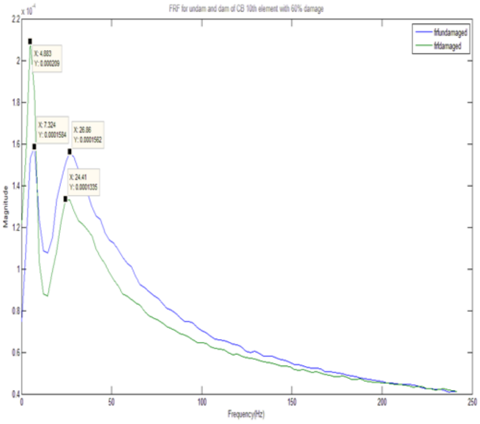

Fig. 3 FRF for 11th Node Sensor

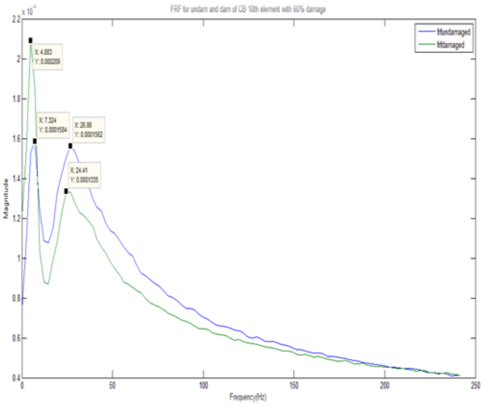

Fig. 4 FRF for 16th Node Sensor

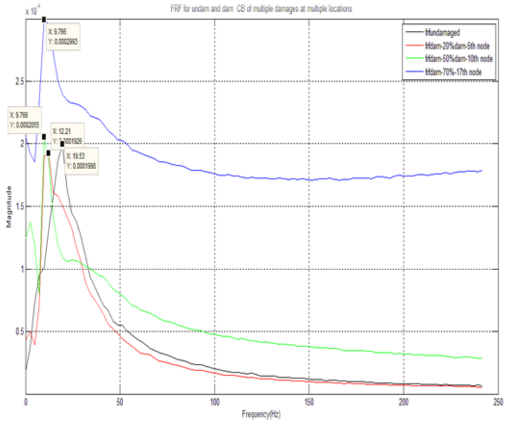

Fig.5FRF for Multiple Damage Cases

It can be clearly observed from the above figures that there is change in magnitude (peak amplitudes) of FRF for all damaged cases when comparing with undamaged FRF.We can also observe the clear shift in the resonance frequencies in the FRF plots for all damaged cases with respect to undamaged cases as tabulated in natural frequency Table.3

The changes in FRF plots and natural frequencies between the undamaged and damaged states indicate the presence of damage in the beam.

The FDAC value is calculated for each sensor for the wide range of frequencies depending up on the FFT length used for the Fourier transformation and then severity of the damage is estimated using proposed severity index.

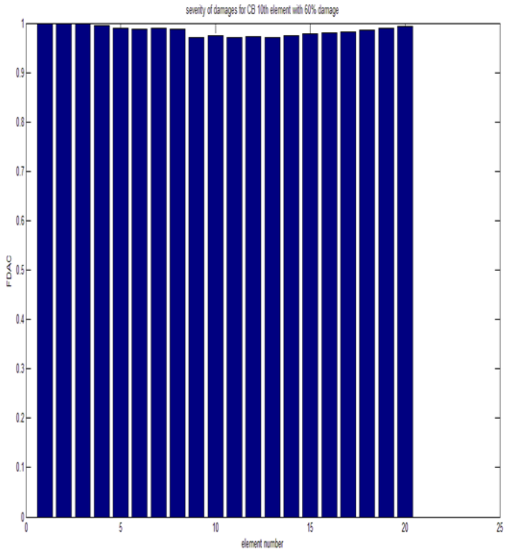

Fig.6 Severity of Damages for 11th Node

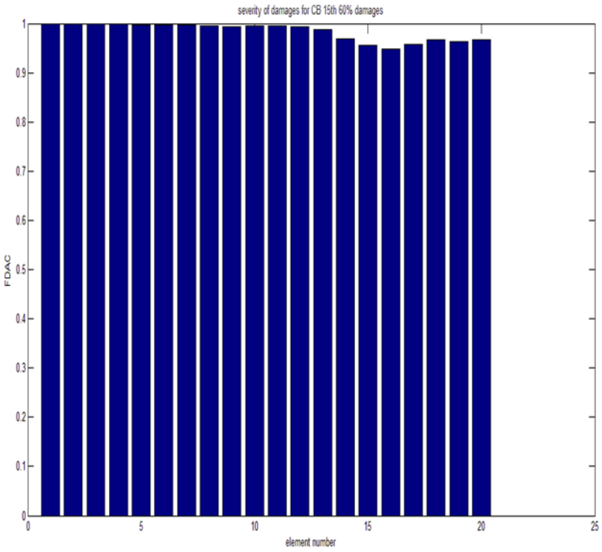

Fig.7 Severity of Damages for 16th Node

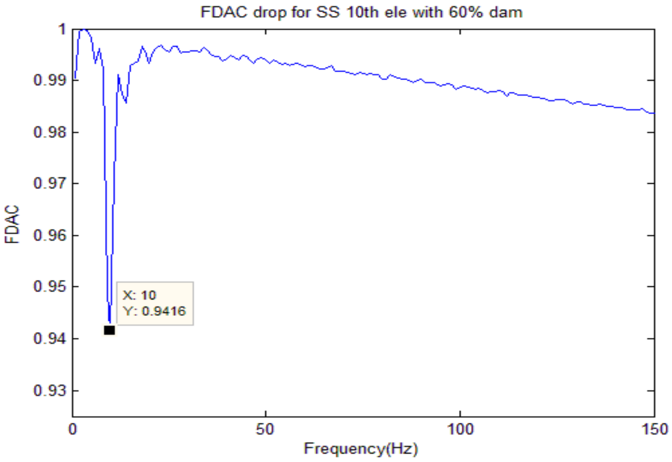

Fig.8FDAC Drop for 11th Node Sensor

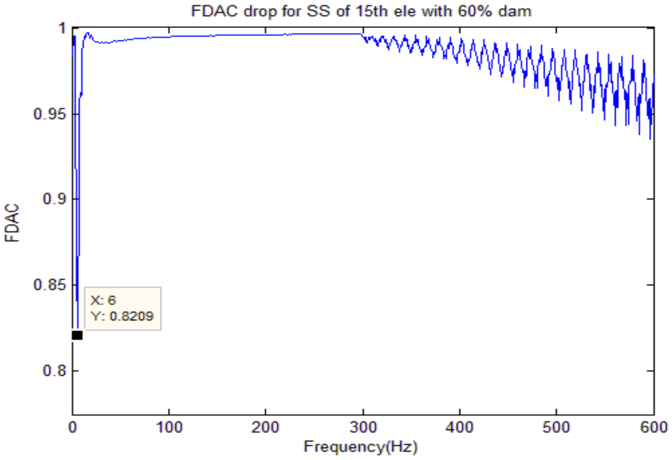

Fig .9 FDAC Drop for 16th Node Sensor

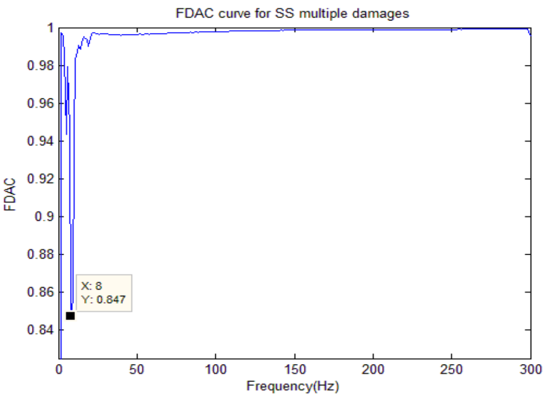

Fig.10FDAC Drop for Multiple Damage Case

The severity of damages and FDAC plot corresponding to 11^{th},16thnode and multiple damage case with multiple locations is shown in Fig6, 7, 8, 9, and 10.

The severity index values shown in Table 4 for damaged cases agreed with simulation. Hence Severity index developed from FDAC is a good indicator to tell the severity of the damage in the structure.

Table. 4 Severity Index Value

Case No.	Severity index value	Severity range
1	0.9416	Medium
2	0.8209	Medium
3	0.8470	Medium

VII. CONCLUSIONS

In this paper a technique based on frequency response function to detect the presence and severity of damage in the structure. The variations of the FRF for the various damaged cases has been illustrated through a numerical example to identify the robustness of the FRF in damage identification. The proposed severity index is found to be a good indicator in quantifying damage. The major advantage of the technique is that frequency response function can be easily measured through experiments accurately and damage is identified and quantified without any further complex processing.

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