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Damage Identification Based on Curvature Mode Shape using Cubic Polynomial Regression and Chebyshev Filters

C M Hasrizam[1*] and Noor Fawazi[1]

[1] Mechanical Precision Engineering, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Semarak, 54100 Kuala Lumpur, Malaysia.
Corresponding author: mhasrizam2@graduate.utm.my

Abstract. Structure Health Monitoring (SHM) has been applied in various application such as aerospace, machinery and civil structures to maintain structure's safety and integrity. Gapped smoothing method (GSM) is most popular non-destructive identification (NDI) method due to its simplicity and did not require baseline data for comparisons. However, GSM is less accurate to detect wide size of damage in structure and cause false detection. Objective of this study is to propose a method to detect damage in structure using curvature mode shape data estimated from damaged structure and did not require data from undamaged structure. Finite element analysis (FEA) on a free-free boundary condition steel beam was carried out to demonstrate the feasibility of the proposed method that estimate undamaged curvature mode shape data using cubic polynomial regression (CPR) and Chebyshev filters (CF) methods. The results shows proposed method that used Chebyshev filters has better accuracy damage detection on wide notch compared to GSM. Although application of an interpolation and Chebyshev filters showed results with a high potential for overcoming the issue of false detection due to different notch size, however the proposed method still need refinement to better detection of different damage cases.

1. Introduction

Structure Health Monitoring (SHM) is one of important tools to maintain safety and integrity of structure such as aircraft, automotive, machinery, multi-storey building and bridges [1-4]. A reliable non-destructive identification (NDI) is important to ensure effectiveness of such monitoring system. Because undetected damage may grow and reduce structure integrity which subsequently lead to catastrophic failure.

Vibration-based damage detection method has been studied extensively in the past few decades [5]. This method was based on physical changes in structures which manifest by changes in modal parameters (i.e. natural frequencies, mode shape and damping coefficient). Therefore, the changes of modal characteristics in structures can be treated as the damage indicator.

Study by Ratcliffe [6] shows curvature mode shape as parameter to detect damage in structure by using the mode shape data from undamaged and damaged structures, and they are found curvature mode shape can be better indicators for damage identification compared to natural frequency. However this method requires data from the undamaged structures which may impossible to be obtained in real life structure. Wahab and Roeck [7] has extended the curvature mode shape method by averaging the damage index over all modes and applied their technique to a concrete bridge. Gapped Smoothing Method (GSM) was introduced by Pandey *et.al* [8], advantage of the GSM compare to other methods it did not require data from the undamaged structures. However, this method not accurate to detect big size crack because the damage index will create 2 peaks which indicate presence of the two small size cracksinstead of one big size crack [9].

This paper will propose a method to detect damage in structure using curvature mode shape data from damaged structure and did not require data from undamaged structure. This technique will used small number of measurement data to estimate undamaged curvature mode shape data, ω_u using cubic polynomial regression (CPR) and Chebyshev filters (CF) methods. The data subsequently used to calculate damage index in order to determine location and size of the damage in structures. This method is expected to enable detection of wide size of crack without data from undamaged structures.

2. Methodology

2.1. Finite Element Analysis

For this study, geometry of the beam is same as used by Pandey *et.al* [8]. Figure 1 shows a diagram of a steel beam model with notch to represent damage that was used in the study. The model has dimension of 914.4 mm in length, 6.35 mm in height and 50.8 mm in width (36 in x 2 in x ¼ in). The mode shape data are obtained at a total of 36 grid points located from 12.7 mm to 901.7 mm by a grid spacing (Δx) of 25.4mm along the distance. 12.7 mm narrow notch with node 12 at the centre of the notch and the node 12 was located 292.1 mm from one end are introduced at bottom of the beam to represent the narrow notch damage. In addition, 127 mm wide notch with node 13 at the centre of the notch and the node 13 was located 317.5 mm from one end are introduced at bottom of the beam to represent the wide notch damage. The depth for both notch type is 0.1905 mm or 3% from total beam thickness.

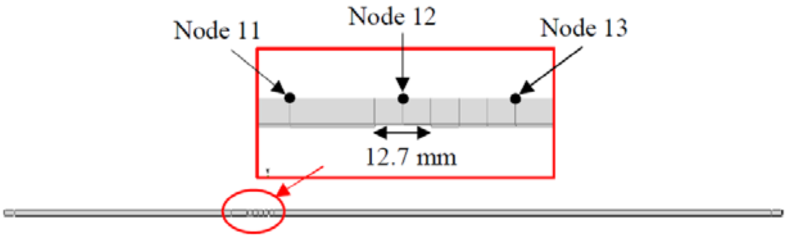


Figure 1. Diagram of the Beam and Notch Location (Narrow Notch).

Finite element analysis (FEA) was performed using commercial code ABAQUS to obtain the vibration responses of the steel beam models. Three-dimensional continuum solid elements with 20 nodes with reduced integration and second order accuracy (C3D20R) are used to discretize the model. The model has isotropic material properties with Young Modulus, density and Poisson's Ratio are 204.9 GPa, 7850 kg/m^3 and 0.3 respectively. Both cases have free-free boundary condition and the first bending mode shape was used for data processing.

2.2 Data Analysis Procedures

Data analysis process for this study is presented in this section. Two beam with different damage cases were considered in this study, namely narrow notch and wide notch. Firstly, displacement mode shape data, $U_2$from 14 nodes was obtained from FEA performed as explained in section 2.1. Later, the displacement mode shape data, U_2 was interpolated into 36 nodes using Barycentric interpolation (n=2) equation as follows:

$$f(x) = \frac{(x-x_2)(x-x_3)\dots(x-x_n)}{(x_1-x_2)(x_1-x_3)\dots(x_1-x_n)}y_1 + \frac{(x-x_1)(x-x_3)\dots(x-x_n)}{(x_2-x_1)(x_2-x_3)\dots(x_2-x_n)}y_2 + \cdots + \frac{(x-x_1)(x-x_2)\dots(x-x_n)}{(x_n-x_1)(x_n-x_2)\dots(x_n-x_{n-1})}y_n \quad (1)$$

Secondly, the curvature mode shape data, ω_u was estimated using interpolated displacement mode shape data, U_2throughcentral finite different equation [8]:

$$curvature\ mode\ shape, \omega_i = \frac{u_{i-1} - 2u_i + u_{i+1}}{\Delta x^2} \tag{2}$$

where u_i is mode shape at the grid point *i* and Δx is the distance between two successive grid points.

Thirdly, the interpolated curvature mode shape data fitted using two method, cubic polynomial regression and Chebyshev filters. Through this process, fitted curvature mode shape will be used as undamaged curvature mode shape data. The undamaged curvature mode shape data fitted with cubic polynomial regression is called $\omega_{u(\mathrm{CPR})}$ and the undamaged curvature mode shape data fitted with Chebyshev filters is called $\omega_{u(\mathrm{CF})}$. Subsequently, modal curvature difference or damage index was by subtracting the undamaged curvature mode shape, ω_u from the damaged curvature mode shape, ω_d (calculated using displacement mode shape data, $U_2$from 36 nodes obtained from FEA performed as explained in section 2.1), given by:

$$Damage\ Index, \delta_i^m = |\omega_d]_i - \omega_u]_i| \tag{3}$$

where $\omega_d]_i$ and $\omega_u]_i$ are curvature mode shape dataat the grid point *i*of the damaged and undamaged structures respectively.

3.Result and Discussions

3.1. Natural Frequency

Table 1 shows natural frequency data from FEA and experimental data [9] for narrow notch beam. Only the fundamental bending mode shapes are considered for data processing. The difference between experiment and FEA is less than 3% for the first four bending mode shapes, it indicates that the data from FEA has good correlation with experimental data.

Table 1. Natural frequency data from Present FEA and experimental data by Wahab and Roeck [9].

Mode Shape	Natural Frequency, $\boldsymbol{\omega_n}$ (Hz)		Difference, $\Delta\boldsymbol{\omega_n}$ (%)
	Experiment (Ratcliffe, 2009)	Present FEA	
1	39.092	39.884	2.03
2	108.640	109.96	1.22
3	210.108	215.62	2.62
4	352.940	356.55	1.02

3.2 Curvature Mode Shape

Curvature mode shape is the data that was obtained by differentiating the displacement mode shape data twice, for this study the curvature mode shape was approximated using central different finite different of the displacement mode shape data.

Figure 2 shows plot of curvature mode shape, it was noted that curvature mode shape for undamaged beam has clean shape from any irregularity while the narrow notch has very small irregularity that not clearly visible, and the wide notch has big irregularity that clearly observable.

Thus, differences in curvature mode shape between damage and undamaged can show damage location in the structures.

Table 2 shows standard deviation for narrow notch and wide narrow that use cubic polynomial regression and Chebyshev filters fitting methods. It was noted that Chebyshev filters fitting method has better approximation undamaged curvature mode shapes compared to cubic polynomial regression. Better approximation for Chebyshev filters fitting method because the method remove unwanted components before fitting the data, while cubic polynomial regression only fitting the data. Thus, Chebyshev filters fitting method can detect damage location more accurate compared to cubic polynomial regression.

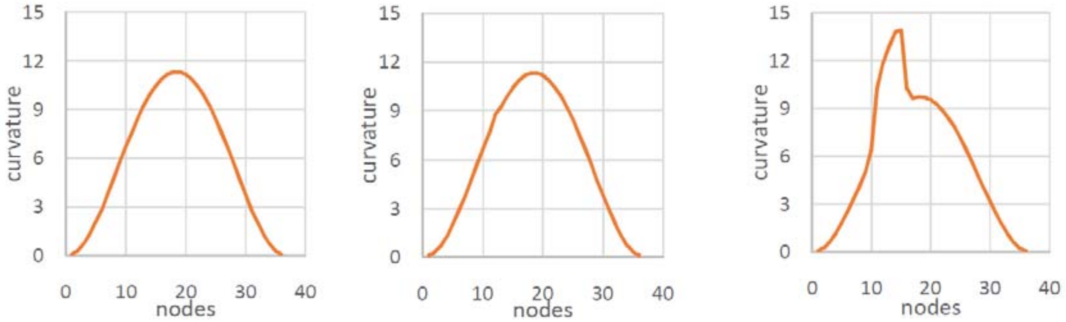
3.3. Damage Index

Damage index plot is an indicator to show presence of damage in the structure. It was calculated by subtracting the undamaged curvature mode shape, ω_u from the damaged curvature mode shape, ω_d. In addition, size and location of crack in the structure can be estimated from damage index plot. Figure 4 shows damage index for narrow notch cases. It was noted, GSM and Chebyshev method able to determine damage location accurately while Cubic polynomial regression unable to detect damage location.

Figure 5 shows damage index plot for narrow notch case. From this figure, GSM indicates presence of two nearby small notch at node 11 and node 15 which is false detection. Cubic polynomial regression indicates presence of wide notch in between node 11 to 15, however this method indicate presence of another wide notch in between node 5 to 10 which is false detection. Among all method, only Chebyshev filters method can predict presence of wide notch in between node 11 to 15 accurately.

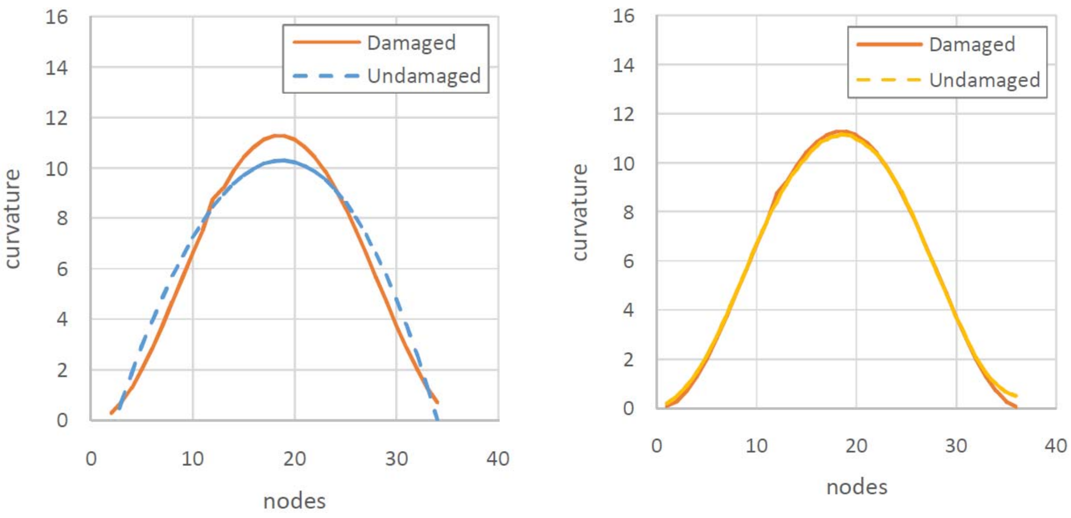
Different in damage detection capability between GSM and proposed method (cubic polynomial regression and Chebyshev filters) is due to lack of curvature change at node 12, 13 and 14. It caused GSM to only detect damage at sudden changes (node 11 and 15) in curvature mode shape plot which later indicated as two small damage in damage index plot.

On the other hand, since Chebyshev is a filter that removes unwanted components in interpolated undamaged curvature mode shape data, it also capable to create more smooth approximation of undamaged curvature mode shape compared cubic polynomial regression. Lack of filter capability caused cubic polynomial regression to have deviation in curvature mode shape data than damaged curvature mode shape and the different is indicated in damage index as false damage detection. Hence, Chebyshev method capable to smooth the interpolated curvature mode shape data to estimate the undamaged curvature mode shape data more precisely allows it to detect wide notch type of damage in structure.

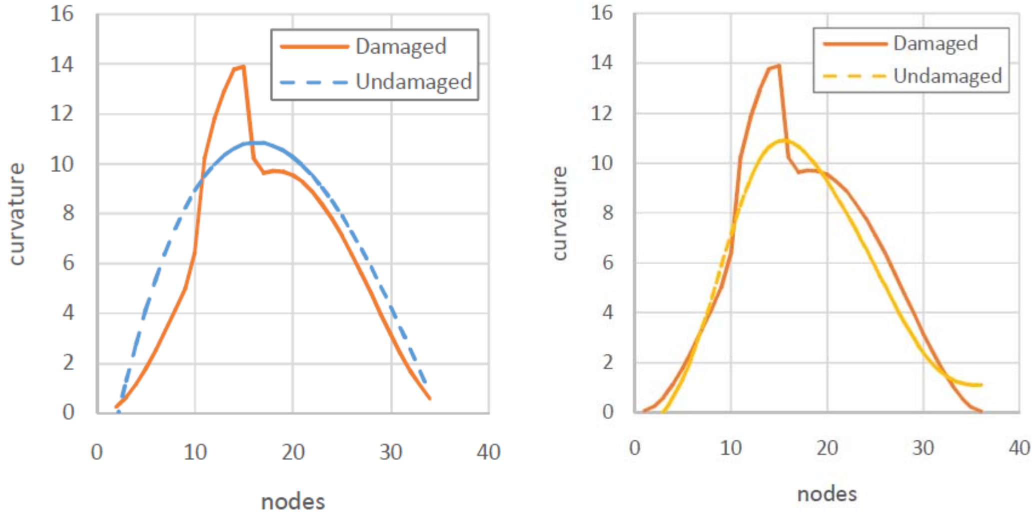


a) undamaged b) narrow notch c) wide notch

Figure 2. Curvature mode shape plot for a) undamaged, b) narrow notch and c) wide notch.



a) narrow notch - CPR b) narrow notch - CF

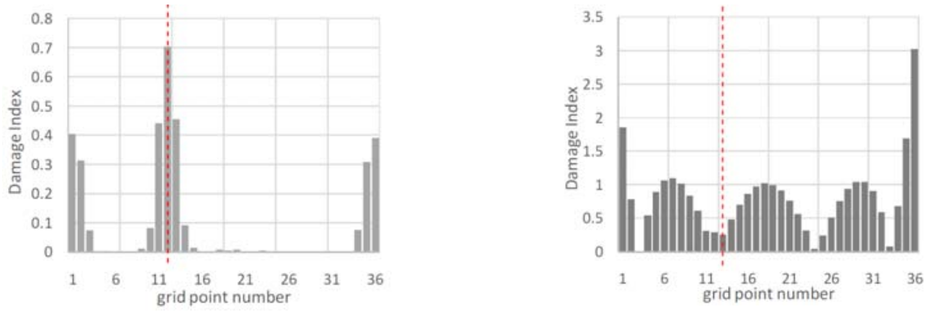


c) wide notch - CPR d) wide notch - CF

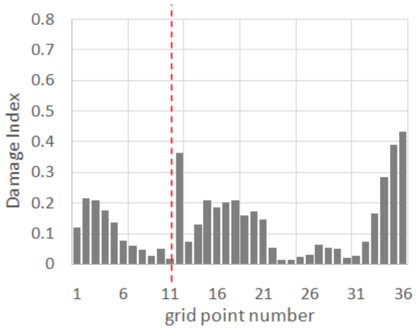
Figure 3. Curvature mode shape plot for narrow notch and wide notch.

Table 2. Standard Deviation for different Fitting Methods.

	Standard Deviation	
Fitting Method	Narrow Notch	Wide Notch
Cubic Polynomial Regression (CPR)	6.7210	6.1449
Chebyshev Filters (CF)	0.1718	1.2576

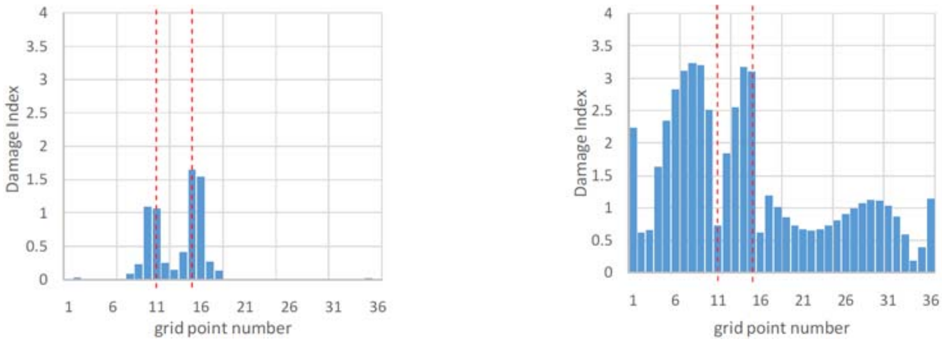


a) GSM b) CPR

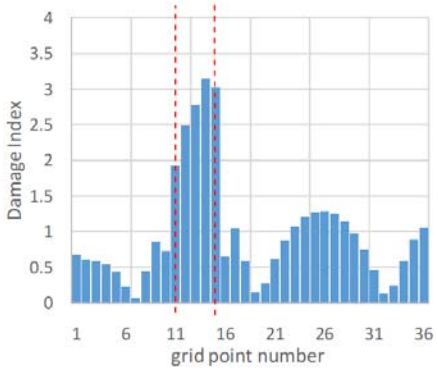


c) CF

Figure 4. Damage Index plot for Narrow Notch for a) GSM, b) CPR and c) CF.



a) GSM b) CPR



c) CF

Figure 5. Damage Index plot for Wide Notch for a) GSM, b) CPR and c) CF.

4. Conclusion and future work

This paper proposed new method to estimate undamaged curvature mode shape data using damaged curvature mode shape data using cubic regression and Chebyshev filter. Numerical analysis has been conducted using steel beam with 3% damage and narrow and wide notch to demonstrate the feasibility of proposed method.

For narrow type notch, GSM and Chebyshev filters able to determine damage location accurately while Cubic polynomial regression unable to detect the damage location. However, Chebyshev filters create some noise that can lead to fault detection. For wide type notch GSM and cubic polynomial regression can predict location however not the size of the crack in structure while only Chebyshev filters method can predict presence of wide notch in between node 11 to 15 accurately. Unlike GSM and cubic polynomial regression method, Chebyshev filter is able to estimate undamaged curvature mode shape near to actual undamaged data. This is because Chebyshev filter only remove unwanted component in the data whilst maintain the shape of curvature mode shape.

However, this study is only limited to one type of filter. Hence, damage detection using other filter or other smoothing formulation to estimate undamaged curvature mode shape that closer to actual undamaged data is recommended for future study.

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