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A REVIEW OF VIBRATION BASED STRUCTURAL HEALTH MONITORING USING MODAL DATA AND WAVELETS

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ABSTRACT

A brief review on vibration based damage identification methods for different types of structures were explained. Identification and localization of damage in the structure is a challenging task, Health monitoring techniques of static and dynamic structures are very significant. Frequency, Mode shape, Mode shape curvature and wavelets based damage detection methods are very few familiar techniques in crack detection. Following methods are using the modal parameters (mode shapes and frequencies) of the structure. Vibration based crack detection techniques. Locate and estimate the damage events by comparing the dynamic responses between damaged and undamaged structures. According to the dynamic response parameters analyzed, these methods further sub divided into modal analysis, frequency domain, time domain and impedance domain. Model-dependent methods were able to find global and local damage information. This paper investigates the impact of more than eighty articles on vibration based damage detection. These methods were cost effective and relatively easy to use, however, there are still many challenges and obstacles are there before these methods to implemented in practice

Key words: Frequency, Mode shape, Mode shape curvature, Wavelet transform, Damage detection.

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1. INTRODUCTION

Structural damage in the structure cost many lives in past so structural monitoring in the civil engineering field and aerospace industries are rapidly developing last few decades, so structural control has been attracting the concentration and attention of researchers over the past several decades. Vibration based structural health condition monitoring, it is classified into two methods like active and passive structural control is structural health monitoring. Housner et al (1997) highlights health monitoring refers to the use of in-situ, nondestructive sensing and analysis of system characteristics, including structural response, for the purpose of detecting changes, which may indicate damage or degradation. Like structural control, health monitoring of civil structures is a very active area of both academic and industry research and development. Measurements of strain, acceleration, velocity, displacement, rotation, and other parameters have always been a primary tool in engineering, so the concept of experimental monitoring is certainly not new to civil engineering. Rytter (1993) classified the various methods based on the level of identification attempted:

Level 1: Determination that damage is present in the structure

Level 2: Determination of the geometric location of the damage

Level 3: Quantification of the severity of the damage

Level 4: Prediction of the remaining service life of the structure

However, recent developments in measurement, communications and computational technology facilitate the application of health monitoring of large structures. These technological developments include new and improved sensors, high-resolution digital data acquisition, digital communications technology, and real-time computational capability. In conjunction with recent analytical developments, they hold the promise of early damage detection at both local and global scales on large civil structures. The following sections give an overview of recent developments in the field of structural health monitoring. Case studies are presented along with a discussion of research needs specific to this field.

2. FREQUENCY CHANGE

Cawley and Adams (1979) proposed a new idea about how measurements made at a single point in the structure can used to detect and quantify damage. Formulate the damage detection techniques in composite materials from frequency shifts.

Table I explains the natural frequencies of trapezoidal plate are reducing due to the damage present in the structure (Cawley and Adams 1979).

Damage	Undamaged Frequencies (Hz)										% of defect
	104.32	260.98	312.74	415.29	584.48	693.24	794.70	936.50	1062.25	1150.93	
	Frequency reductions from virgin condition(Hz)										
1 saw cut	0.06	0.39	0.29	0.14	-0.07	0.14	2.70	0.62	0.20	0.28	0.19
2 saw cut	0.85	5.46	4.50	2.08	1.78	4.32	5.29	3.70	1.20	1.68	2.17
3 saw cut	1.24	5.66	5.91	3.44	3.93	4.38	9.02	6.90	10.41	6.51	3.65

Wolff and Richardson (1989) investigated flat plate with a rib stiffener bolted structure used as the test specimen. It is shown how modal parameters can detect variations in the bolt tightness between the plate and the rib.

Table II (a, b) shows natural frequencies are reducing after removal of the bolt it denotes the sensitivity of modal parameters. (Tom Wolff and Mark Richardson 1989)

MODE	With Bolt FREQ(Hz)	Without Bolt FREQ(Hz)	DIFFERENCE
1	106.687	105.635	-1.052
2	190.636	190.186	-0.450
3	247.650	242.994	-4.656
4	259.222	254.200	-5.022
5	261.955	260.137	-1.818
6	470.489	466.324	-4.165
7	494.482	484.482	-10.328

(a)

MODE	With Bolt FREQ(Hz)	Without Bolt FREQ(Hz)	DIFFERENCE
1	106.687	103.796	-2.891
2	190.636	188.184	-2.452
3	247.650	233.385	-14.265
4	259.222	242.108	-17.114
5	261.955	259.559	-2.396
6	470.489	442.153	-28.336
7	494.482	464.330	-30.48

(b)

Adams et al (1991) investigated GRP space lattice structures and concluded modal parameters are very effective in composite .This method is useful to detect various forms of damage such as severed members, delimitation and crushing. Swamidas and Chen (1995) performed modal analysis on cantilever plate with a small crack, and suggested surface crack in the structure affected most of the modal parameter. Nandwana and Maiti (1997) proposed frequency based damage detection for stepped cantilever beam. Crack is represented as a rotational spring. Crack size is computed the standard relation between stiffness and crack size. Mahumoud and Abukeifa (1998) presented a novel technique called GRNN, the general regression neural network method using the natural frequency to localize the defect and also quantify it. It is simple compare to BPN (back propagation network).

Fig.1 Present the crack size (a/h) and the crack location (x/L) in cantilever beam size of (0.0125X0.0125X0.57); it suggest more than two natural frequencies need for estimate crack size and location.

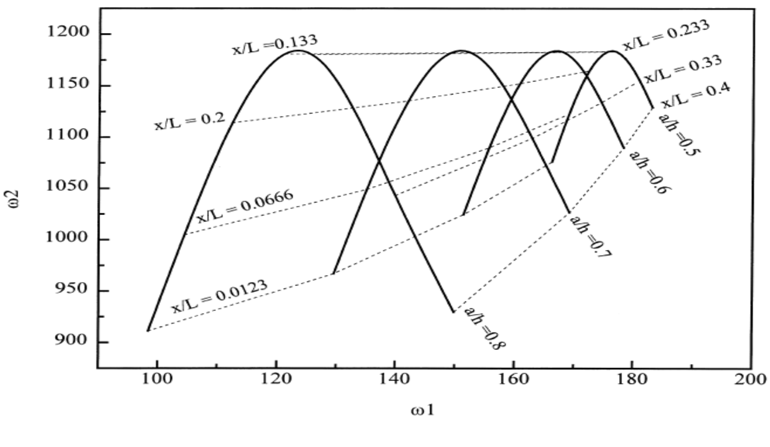
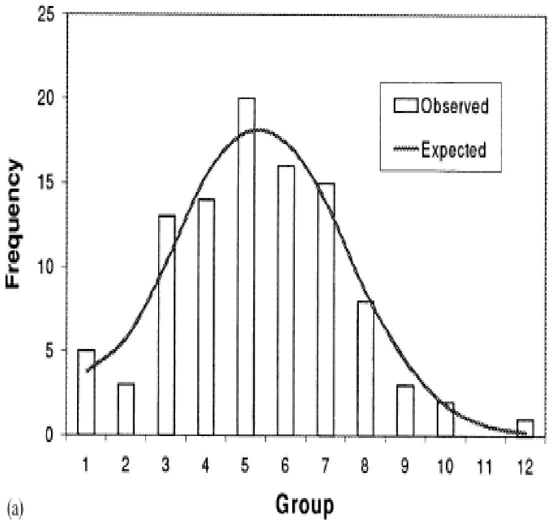


Figure 1 Nomo graphs of ω_1 and ω_2 for different crack sizes (a/h) and crack locations(x/L) **(**Mahumoud et al 1998)

Xia and Hao (2003) developed a statistical damage identification algorithm based on changes in natural frequency in presence of random noise in both the vibration data generated by finite element model.



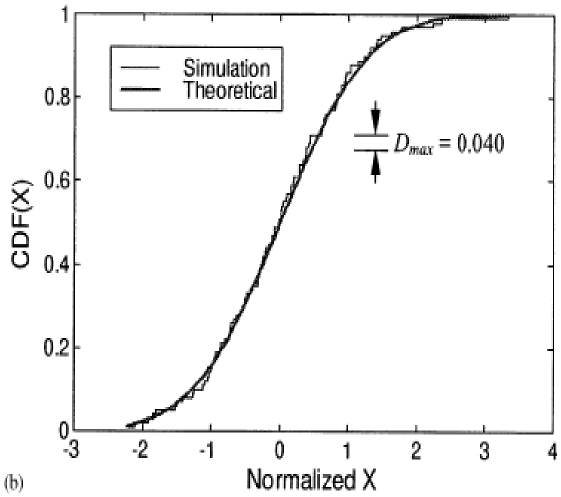


Figure 2 (a) Chi-square goodness-of-fit tes **Figure 2 (b)** K–S goodness-of-fit test. (Xia and Hao 2003)

Fig 2(a) shows the comparison of observed and theoretical frequencies of the non-overlapping groups, Fig.2(b) explains the cumulative distribution function (CDF) calculated from the sample points as compared with the theoretical one. Based on the goodness-of-fit test approach, normal distribution hypothesis of the stiffness parameters for all the elements is accepted with a confidence level of 95%. Murat kisa (2003) exposed the effects of cracks on the dynamical characteristics of a cantilever composite beam. Haldar et al (2008) proposed GILS-EKF-UI (Generalized Iterative Least square-Extended Kalman Filter-Unknown Input) method based on dynamic response technique this method localize the defect location accurately without excitation only noise contaminated response is sufficient. Lam and Yin (2010) proposed two phase multiple crack detection in plate structure crack is identified by Bayesian model class selection method, crack parameters like locations and crack size evaluating process was verified probability density function. Mazanoglu and Sabuncu (2012) Proposed new algorithm that uses the map of the natural frequency ratio and processed through the recursively scaled zoomed frequencies it uses the cubic spline interpolation method for obtained increased solution. Guirong Yan et al (2013) shows the procedure for identifying the existence of breathing fatigue cracks and quantifying the cracks qualitatively is proposed by looking for the difference in the identified natural frequency between regions. Hilbert transform is extended to identify fatigue cracks in piecewise-nonlinear systems. Mehdi karimi et al (2013) crack detection in blades using the combination of natural frequency and neural network system to find the crack location and depth of the crack. Sachin K. Singh and Rajiv Tiwari (2014) implement vibration based crack detection in shaft using the slope discontinuities in the shaft elastic line. Lourdes Rubio (2015) explained the inverse problem of identifying a single crack in a longitudinally non symmetric vibrating rod by minimal frequency data. Nandakumar and Shankar (2015) proposed novel technique in damage detection for multi story building structure based on transfer matrix. (Labib et al (2015) proposed natural frequency degradations for locating a single crack in a frame. Wittrick Williams algorithm explained in crack detection.

The most appealing feature associated with using natural frequencies is that the natural frequencies are relatively easy to obtain and easy to extract. The frequency measurement can be quickly conducted with high accuracy. Another advantage is its global nature of the identified frequencies; thus allowing measurement points to be customized at will. However, it is common view that the frequency shift is not sensitive to the local damage. Significant damage may cause very small changes in natural frequencies, particularly for large structures, and these changes may be undetectable due to measurement or processing errors. Variations in the mass of the structure or measurement temperatures may introduce uncertainties in the measured frequency changes. In an attempt to overcome these difficulties, research efforts have been focused on alternative indicators such as changes in mode shapes. One of the attractive features is that changes in mode shape offer more insight in to the location of the damage.

3. MODE SHAPES

Used in conjunction with natural frequencies, mode shapes approach has also received considerable attention in the literature. Chen and Garba (1987) developed a theory for assessing the occurrence, location, and extent of potential damage utilizing on-orbit response measurements. Rizos et al. (1990) explained a method of measuring the amplitude of a cracked steel beam at two points during forced vibration at one of its natural frequencies. Analytical results and experimental mode shapes are compared, the maximum error in location and severity of the crack was no large than 8% and in most cases less than 5%.

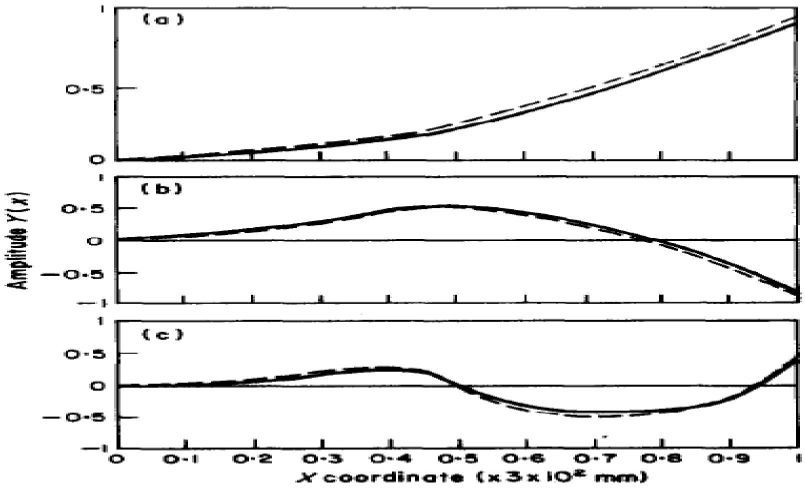


Figure 3 Comparison of measured (- - -) and calculated (———) results for the lowest three vibration modes.(a) First mode, 171 Hz; (b) second mode, 987 Hz; (c) third mode, 3034 Hz. Rizos et al. (1990)

Fig3. Explains vibration modes change with respect to uncracked beam for each vibration mode, depending on the crack location, predicted and measured values almost similar. Measured mode shapes for the first three frequencies of vibration for crack depth 10 mm at position 140 mm from the clamped. Farrar and James (1997) proposed a novel curve-fitting cross-correlation functions to obtain modal properties it was better than standard procedures for estimate the resonant frequencies and modal damping of the structure. Ren and De Roeck (2002a) explained a damage identification method based on changes in frequencies and mode shapes of vibration for predicting damage location and severity. Liu et al. (2003) used a vibration-based technique to evaluate the structural integrity using mode coupling property. Maia et al. (2003) suggested a new version of mode shape- based method by generalizing them to the whole frequency ranges of measurement. The experimental results showed a certain degree of agreement.

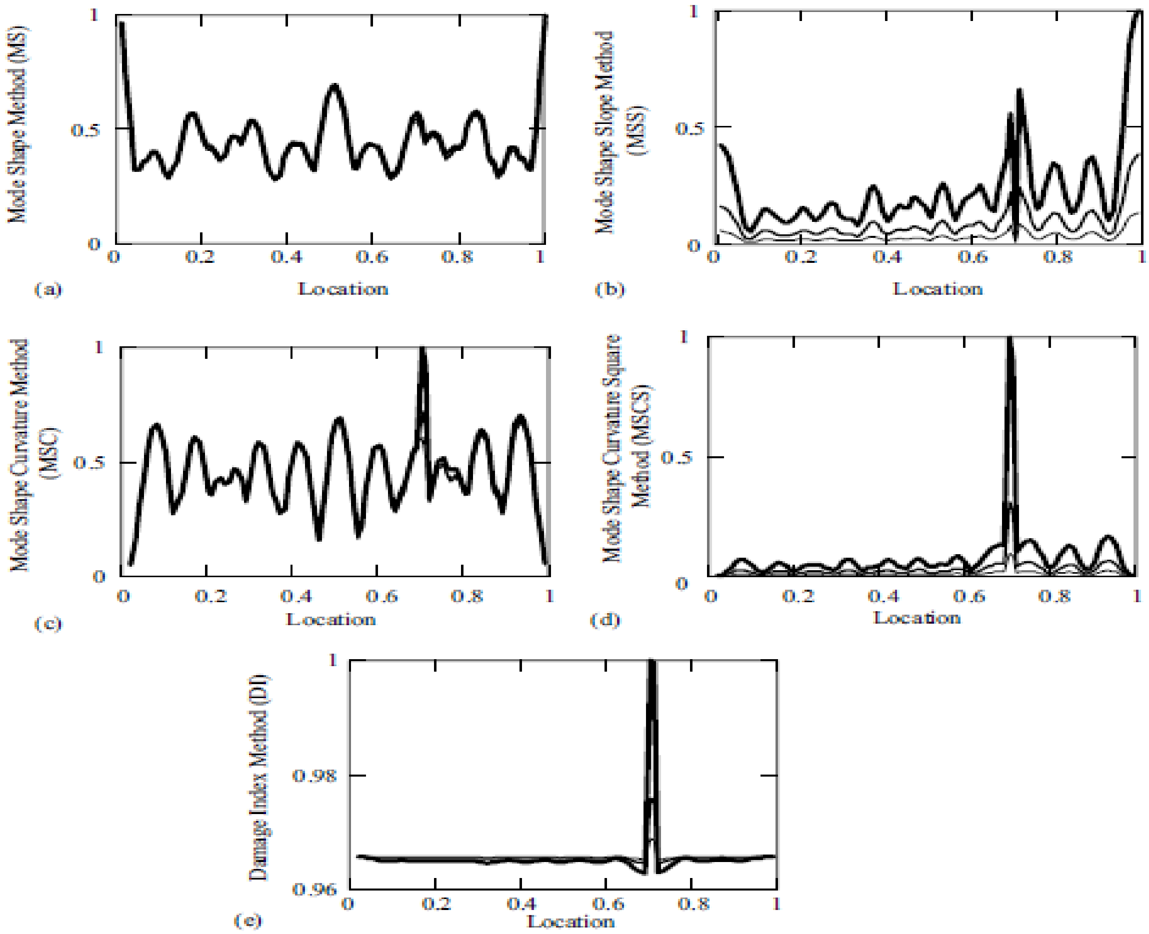


Figure 4 Mode shape damage detection methods (data of first 11 modes). (a) Mode shape method; (b) mode shape slope method; (c) mode shape curvature method; (d) mode shape curvature square method; (e) Damage index method. (Maia et al. 2003)

Fig4. Shows comparing to all methods mode shape methods were capable of pinpointing the damage location, for that higher order derivatives increases the probability of damage detection accuracy. Kim et al. (2003) presented comparison between a frequency based and mode shape-based method for damage identification in beam like structure. FRF based damage detection is producing less error compared mode shape method. Experimentally conclude it.

Table III a Damage prediction results of test beam using MBDD. **(**Kim et al. 2003)

Damage Case	Inflicted damage			Predicted damage		
	DDM element	**Location(x/L)**	**Severity (ΔEI/EI)**	**Range of DDM elements[Location]**	**Most Probable DDM element [Location]**	**Severity (ΔEI/EI)**
CL1	72	0.248	-0.24	51-81[.191-.280]	67 [0.233]	-0.074
CL2	72	0.248	-0.59	51-81[.191-.280]	67 [0.233]	-0.364
CL3	72	0.248	-0.78	51-81[.191-.280]	67 [0.233]	-0.509
CM1	144	0.498	-0.24	133-155[.48-.52]	144[0.498]	-0.132
CM2	144	0.498	-0.59	133-155[.48-.52]	144[0.498]	-0.538
CM3	144	0.498	-0.78	133-155[.48-.52]	144 [0.498]	-0.788

Table III b. Damage prediction results of test beam using FBDD. (Kim et al. 2003)

Damage Case	Inflicted damage			Predicted damage		
	DDM element	Location(x/L)	Crack size (a/H)	DDM elements	Most Probable DDM element [Location]	Crack size (a/H)
CL1	72	0.248	0.09	69,219	0.283,0.759	0.141,N/A
CL2	72	0.248	0.27	66,217	0.227,0.752	0.358,N/A
CL3	72	0.248	0.45	61,213	0.210,0.738	0.574,N/A
CM1	144	0.498	0.09	143,144	0.495,0.498	0.110,0.110
CM2	144	0.498	0.27	142,145	0.491,0.502	0.276,0.276
CM3	144	0.498	0.45	141	0.488	0.420,0.420

Table III a & b shows comparison of the Frequency based damage detection & Mode based detection results; Table III a Using MBDD approach to the structure, the predicted locations were almost similar to the inflicted locations (i.e., the cracks near the mid-span) and were within 6.25-cm from the correct locations (i.e., the cracks near the left quarter-span) in the 3.6-m beam span. It was also observed that the severity of the damage could be estimated with a relatively small size error for the cracks inflicted at the mid-span and a relatively large size error for the cracks at the quarter-span. Table III b Using FBDD approach to the structure, the size of crack could be estimated with a relatively small size error for the crack inflicted at the mid-span and a relatively large size error for the crack at the quarter-span.

Parloo et al. (2003) presented a damage assessment method based on the use of mode shape sensitivities and change in mass or stiffness in test structure. With these sensitivities, differences in the dynamical behaviour of the structure in its undamaged and damaged conditions can be translated into damage information the sensitivities are calculated on the basis of the experimentally determined mode shapes, there is no need for a prior finite element model of the test structure. (Teughels and Roeck (2004) described an iterative sensitivity based FE model updating method in which the discrepancies in both the Eigen frequencies and un-scaled mode shape data obtained from ambient tests are minimized. With the trust region strategy and Tikhonov approach to validate a pre-stressed concrete bridge. Bagchi (2005) demonstrated the model updating techniques using the natural frequencies or frequencies and mode shapes of a structure. The matrix update method applied to the finite element models of a three span continuous steel free deck bridge located in western Canada. The finite element models of the bridge constructed using three-dimensional beam and facet shell elements. Results explain the difference between the modal parameters from the model and field tests affect the quality of the model updating process.

Messina et al (1998) extends the work on a correlation coefficient termed the Multiple Damage Location Assurance Criterion (MDLA) by introducing two methods of estimating the size of defects in a structure this paper suggests few natural frequencies sufficient. Khan et al (2000) Experimented the concrete beam structure and explain the modal discontinuities are how utilized in damage detection and proves that structural defects can be detected and located using a continuously scanned laser Doppler vibrometer. Shi et al (2000) extension of the multiple damage location assurance criterion (MDLAC) from (Messina et al 1998), utilize incomplete mode shape instead of modal frequency. The damage detection strategy is to localize the damage sites first by using incomplete measured mode shapes, and then to detect the damage site and extent again by using measured natural frequencies, which have a better accuracy than mode shapes. Abdo and Hori (2002) proposed rotational mode shapes are more effective than displacement mode shapes in damaged detection. Damage is simulated in plate structure is reduced by modulus of elasticity of an element. This method is sensitive even 5% damage also detecting. Hu and Afzal (2006) presented new statistical algorithm, it was implement to extract a damage indicator by computing mode shapes of vibration testing before and after damage in timbers. Different damage severities, damage locations, and number of damages were simulated by removing mass from intact beams to validate the algorithm. Whalen (2008) higher Mode derivatives are more sensitive in the damage detection when the damage is transverse direction if damage is radial means lower mode derivatives is sensitive. Roy and Chaudhuri (2013) suggested a mathematical foundation to show the correlation between a structural damage and a change in the fundamental mode shape and its derivatives. This has been achieved by deriving the expression of a damaged mode shape utilizing a perturbation approach. A cantilever shear beam, discretized into a number of elements, the change in the fundamental mode shape due to any damage is a good indicator of damage localization as it is found to be discontinuous at the location of damage. Proposed method validate with 12 story shear building.

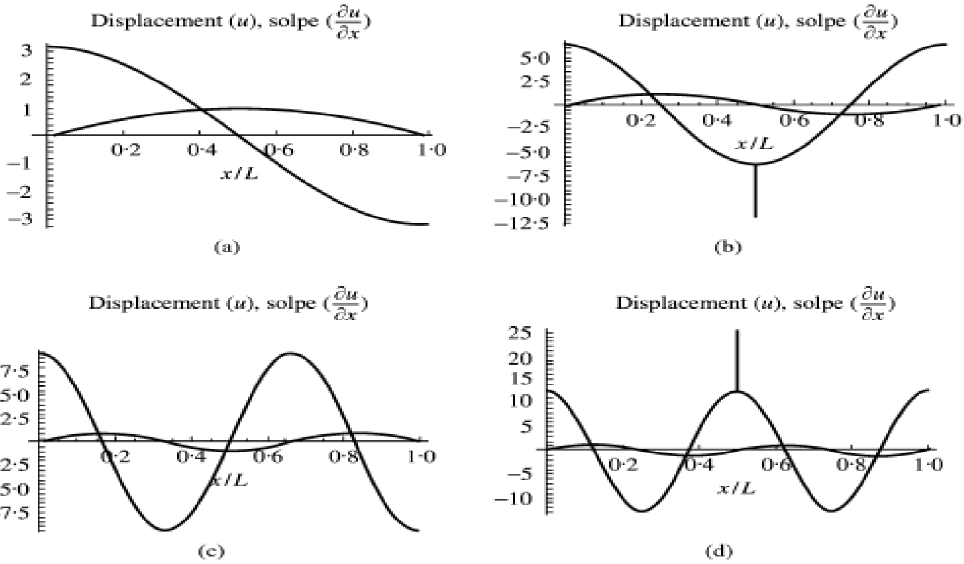


Figure 5 Displacement and slope of mode shapes of a bar element (x_d=0.5L)(a) first mode; (b) second mode; (c) third mode; (b) fourth mode. (Abdo and Hori 2002)

Fig.5 explains the difference between the translational and rotational mode shapes of a beam structure. However, there are some drawbacks on using mode shapes methods: first, it is not an easy task to obtain the meaningful mode shapes, especially for large structures; confident identification of the damage requires proper number of sensors and right choice of sensor coordinates. Another concern is that damage is a local phenomenon and may not significantly influence mode shapes of the lower modes that are usually measured from vibration tests of large structures. Also, extracted mode shapes are affected by environmental noises from such sources as ambient loads and inconsistent sensor locations. Extra care needs to be taken to distinguish damage events from these uncertainty sources.

4. MODE SHAPE CURVATURE METHOD

An alternative to using mode shapes to obtain information about vibration changes is using mode shapes derivatives, such as curvature. The curvature can be obtained by calculation from displacement modal shapes or measuring the curvatures/strain directly. Pandey et al. (1991) proposed mode shape curvature method in FE beam model, displacement functions are converted into curvature functions.

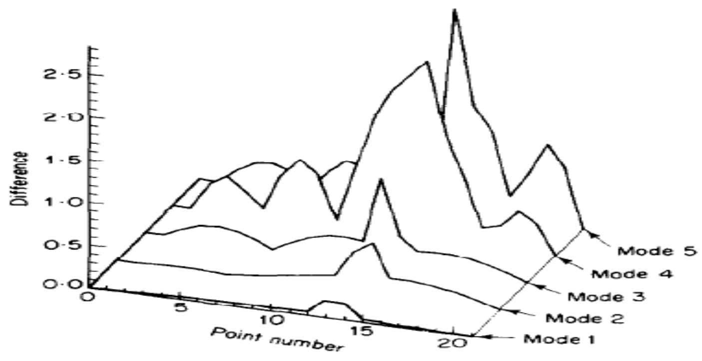


Figure 6 Absolute difference between the curvature mode shapes for the intact and the damaged (element 13) simply supported beam. (Pandey et al. 1991)

Fig. 6 Shows the maximum mode curvature shape difference occur in the damaged location. Higher modes having more sensitivity in damage detection. Chance et al. (1994) explained the bending strain directly proportional to the mode shape curvature. Change in curvature produced by the strain measurement was the most effective way for fault detection. Cornwell et al. (1999) presented a method which required that the mode shapes before and after damage, but it is only limited to structures that are characterized by one dimensional curvature. Hong Hao (2002) explained the genetic algorithm verified with experimental result of cantilever beam.

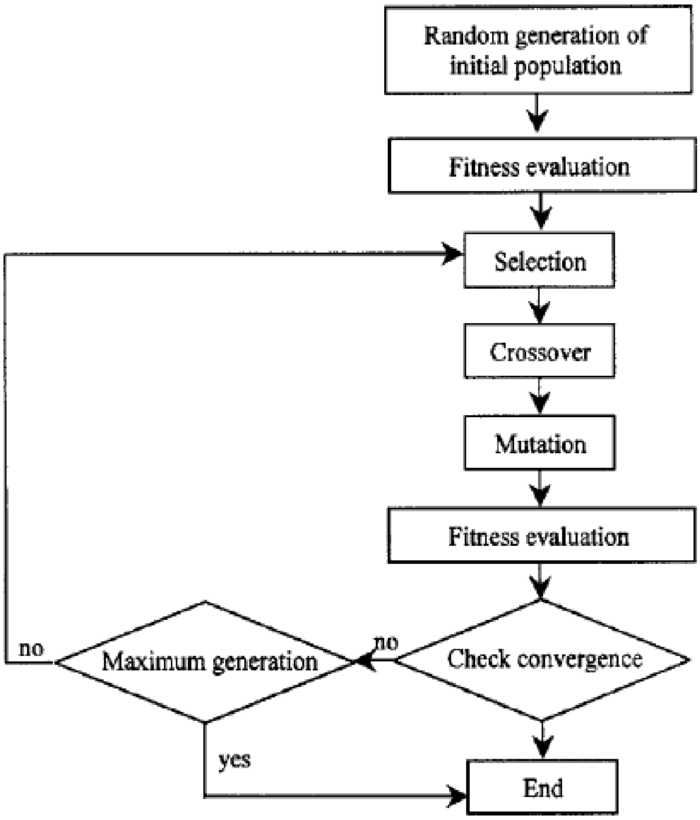


Figure 7 Flow chart of genetic algorithm (Hong Hao 2002)

Fig. 7 Flow chart explains the genetic algorithm step by step proposed method implement in cantilever beam damage detection experimentally verified

Mode shape curvature method is having better sensitive comparing to the Mode shape method in damage detection. The difference of curvature mode shapes from intact and damaged structure can be a good indicator of damage location. The difference in modal curvature shows several peaks not only at the damage location but also at other positions, which may lead to a false indication of damage. In order to reduce the possibility of a false alarm, only first few low curvature mode shapes can be used for damage identification.

5. METHODS BASED ON THE FREQUENCY RESPONSE FUNCTION

Lim et al (1996) experimentally proved the damage present in the truss structure by a real time modal parameter identification algorithm and validated. Wang et al (1997) developed FRF based damage detection technique and implement in 3-bay fame structure and validate the results both numerical and experimentally, and concluded plus or minus 5% error in this method. Sampaio et al. (1999) compared three different types of damage detection methods are named frequency response function (FRF) curvature method , mode shape curvature method and the damage index method. Experimental data from a real bridge were used to demonstrate the application of the proposed procedure. In that process FRF curvature method is performed well in detecting and quantifying damage in the structure. Ratcliffe (2000) explores a narrow slot steel beam damaged structure analysed by FRF. This proposed damage detection method is highly sensitive, and can locate a very small amount of damage. 0.8 percent reduction in thickness in the beam structure also located. Zang and Imregun (2001) proposed the combination of FRF data reduction through the principal component analysis and the inputs are processed to artificial neural networks for damage detection. Lee and Shin (2002) proposed a structural damage identification method based on the frequency response function for beam structures this method is effective even the noise level is 9%. Owolabi (2003) experimentally proved frequency response function is used to detect the damage is aluminium beam structure.

Fanning and Carden (2004) is suggested a single frequency response function measured at several frequencies along with a correlated analytical model of the structure in its original state this method is validate in frame structure. Hwanga and Kimb (2004) proposed FRF method to detect the damage shows numerically evaluated the cantilever beam and helicopter rotor blade. Kwon and Lin (2004) implement the FRF model updating method to detect the damage in rigid rotor bearing system. Santos (2005) utilized FRF sensitivities to detect in the damage in composite rectangular plate structure. Kim and Lee (2010) proposed a method for real fatigue damage detection in a beam structure, exciting force is used to find derivatives. Second spatial derivatives of frequency response functions along the longitudinal direction of a beam are used as the sensitive indicator of crack existence. Baneen et al (2012) In order to avoid noise signal Gapped smoothing method is implement in crack detection, damaged steel beam examined and results are compared with this method. Sinou (2012) Point out the non-linear harmonic components and the emerging anti-resonances in Higher-Order Frequency Response Functions it provide useful information on the presence of cracks and may be used on an on-line crack monitoring system for small levels of damage. Efficiency of the proposed methodology is illustrated through numerical examples for a pipeline beam including a breathing crack. Reddy and Swarnamani (2012) implement the FRF curvature energy damage detection method to the plate structure, the results shows this method is effective 10% damage also localize with presence of noise also.

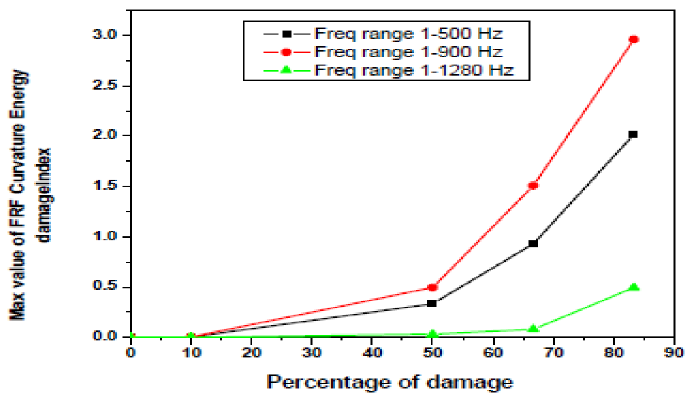


Figure 8 Variation of percentage of damage versus maximum value of FRF curvature energy damage index for different frequency ranges (Reddy and Swarnamani 2012)

Fig.8 Shows Frequency range 1-900 is producing maximum value of FRF curvature Energy it suggests this frequency is very effective in damage detection

$$\Delta\eta = \sum_{\Omega} |\eta^{*}(\Omega) - \eta(\Omega)| \quad (1)$$

$\eta^{*}(\Omega)$: FRF curvature energy of damaged plate.

η (Ω): FRF curvature energy of undamaged plate.

Mohan et al (2013) Compared PSO (Particle Swarm Optimization) with GA (Genetic algorithm). Both techniques are combined with FRF damage detection method. This method is evaluated in the truss and beam structures. From the results PSO implement with FRF is most useful technique in damage detection. Bandara et al (2014) proposed a neural networks-based damage detection method using frequency response function (FRF). Two storey framed structure finite element model formed and verified. Alamdari and Samali (2014) Presented FRFs with Gaussian kernel to suppress the noise during the damage detection, the proposed method experimentally proved with mild steel beam.

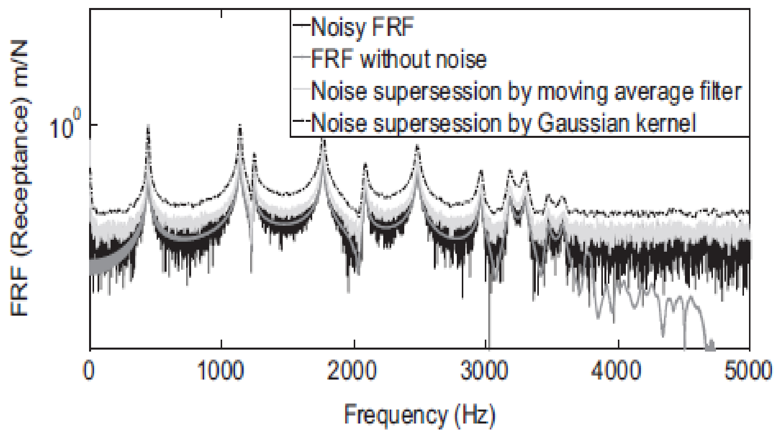


Figure 9.The effect of noise suppression on simulated FRF at a typical dof, 10% noise with exponential distribution in MHLD damage condition (Alamdari and Samali 2014)

A FRF for a typical dof is shown in Fig.10, depicting the effect of 10 percent measurement noise contamination with exponential distribution on simulated FRF. Four plots have been shown in this graph. The noisy FRF is shown by dashed black line, due to noise effect, the FRF is totally smeared in the whole frequency range and the effect of noise is much more visible at points far from the resonances. The noisy FRF is compared with the clean one obtained without consideration of noise effects, dashed gray line. The unpolluted FRF produces clean data even at frequencies far from the resonant points. Noise is suppressed in frequency domain by convolving the noisy FRF with kernel function with smoothing parameter 10; the effect of noise reduction is nicely illustrated in FRF shown with solid black line. Dilena et al (2015) the Interpolation Damage Detection Method is used to give an interpretation of frequency response function (FRF) measurements performed on a reinforced concrete single span bridge subject to increasing levels of concentrated damage. Mode curvature method also compared.

Changes in the structure always monitored by FRF amplitude, damping and frequencies were interpreted as indications of damage. The advantage of continuous real time monitoring is that it gives an operator early warning, so that appropriate action may be taken before a catastrophic failure occurs. Modal data is polluted by modal extraction errors in addition to measurement errors, because they are derived data sets. A complete set of modal data cannot be measured in all but the simplest structures. FRF data can provide much more information on damage in a desired frequency range compared to modal data that is extracted from a very limited range around resonances. Due to localization of damage in structures, techniques using global averaging procedures, applied to changes in Eigen frequencies are less sensitive to initial or small changes. Hence techniques that process the local changes in the structural parameters based on wavelets have emerged. FRF method overcomes the limitations faced in natural frequency and mode shape method. But the force applied location and input force and sensor location are very important in this analysis, so it will narrow the opportunities in damage detection. This method is also effective even noisy environment. When the damage is not able to locate in the structure by FRF method due to its size, Wavelet transforms overcome the problem which present in the FRF. It is detecting the damage using different types of mother wavelets.

6. WAVELET ANALYSIS

The main advantage of using the wavelet transform is its capability to reveal very small or some hidden aspects of the data gathered from a structure that other signal analysis techniques often fail to detect. Staszewski and Tomlison (1994) Proposed wavelet transform method for damage detection in gear teeth. Pattern recognition analysis used for fault detection. Liew and Wang (1998) proposed an application of spatial wavelet theory to damage identification in structures. Wang and Deng (1999) described a method for detecting the location of localized defects. Hou et al. (2000) investigated the characteristics of representative vibration signals under the wavelet transform model is subjected to harmonic force.

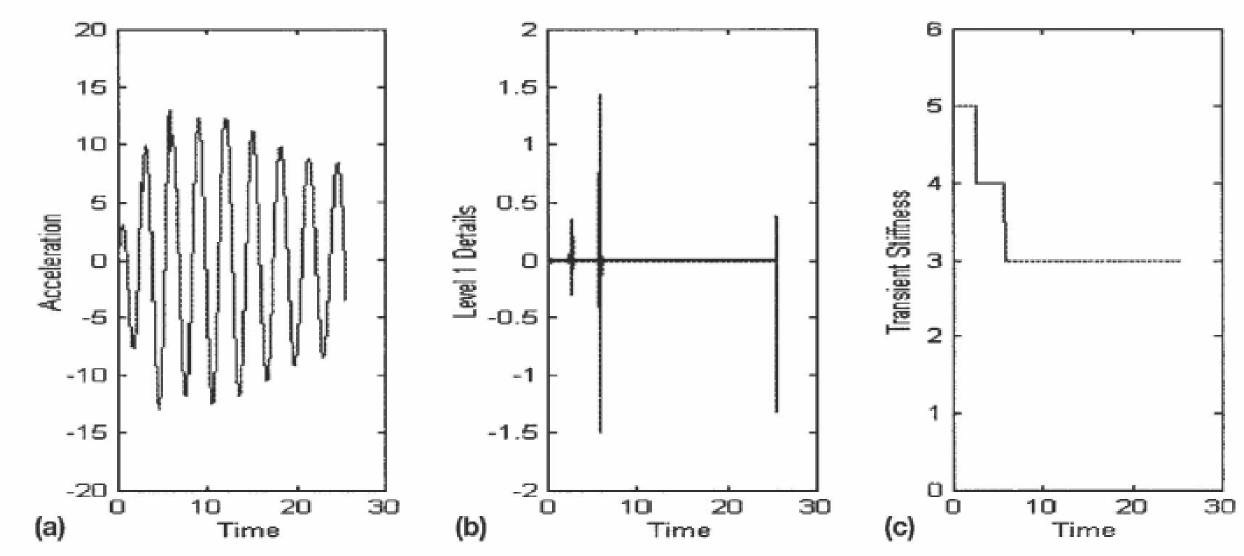


Figure 10 Response of Simple Structural Model to Harmonic Input and Its Wavelet Analysis, Case 1-Damage due to Excessive Response: (a) Acceleration Response; (b) Level 1 Details in Wavelet Decomposition of Acceleration Response; (c) Transient Stiffness History of System (Hou et al. 2000)

Fig. 10 shows there is a failure occurred in spring but Figure (a) shows Acceleration Response cannot identify it, but wavelet decomposition of acceleration response able to identify the defect it is represented in Figure (b) The transient stiffness plot confirmed the damage shown Figure(c).

Quek et al. (2001) implement the wavelet analysis for crack identification in beams with simply supported and fixed–fixed boundary conditions. Abdo and Hori (2001) made numerical study of the relation between damage characteristics and changes in the dynamic properties. It is found the rotation mode shape has the characteristic of localization at the damaged region even though the displacement modes do not localize damage. Edward et al. (2002) suggested method for extraction of localized changes (damage peaks) from strain energy mode shape (SEMS) based on Fourier analysis of the structure energy distribution. A detailed analytical proof is given for the case of a pinned –pinned beam and a numerical proof of the free-free beam. Hong et al. (2002) used the Lipschitz exponent for the detection of singularities in beam modal data. The Lipschitz exponent is sensitive to both sampling distance and noise resulting in limited accuracy of correlation prediction. Hani Melhem and Hansang Kim (2003) explain the comparison of Fast Fourier transform (FFT) and continuous wavelet transform CWT in the structural analysis, and concluded wavelet analysis is applicable damage detection of concrete. Douka et al. (2003) developed a method for crack identification in plate structures based on wavelet analysis. Chang and Chen (2004) used Gabor wavelet transform for spatially distributed modes so that the distributions of wavelet coefficients could identify the damage position on a rectangular plate by showing a peak at the position of the damage. Ovanesova and Suarez (2004) presented applications of the wavelet transform to detect cracks in frame structures, such as beams and plane frames. Chang and Chen (2005) gave a method for damage detection based on wavelet analysis. The innovation of the method is that both the position and depths of multi cracks can be estimated from spatial wavelet based method. Rucka and Wilde (2006) demonstrated estimation of the damage location in Plexiglas cantilever beam and all boundaries are fixed plate structure using wavelet analysis using both experimental and analytical mode shape data. The location of the damage is indicated by a peak in the spatial variation of the transformed response. Applications of Gaussian wavelet for one-dimensional problems and reverse bi orthogonal wavelet for two-dimensional structures are presented. The proposed wavelet analysis can effectively identify the defect position without knowledge of neither the structure characteristics nor its mathematical model.

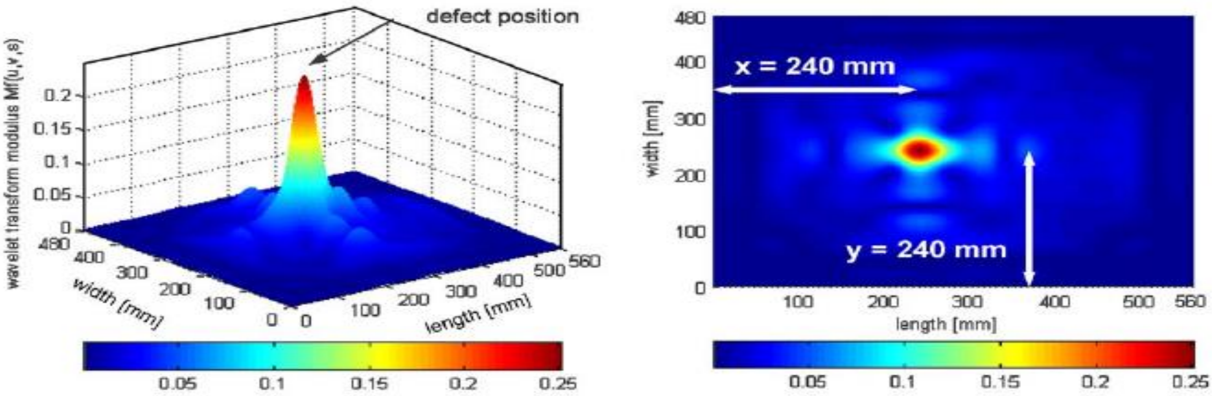


Figure 11 Wavelet coefficients and wavelet transform modulus for the plate using rbio5.5 wavelet based on numerical data.(a) Isometric view b) Top view (Rucka and Wilde 2006)

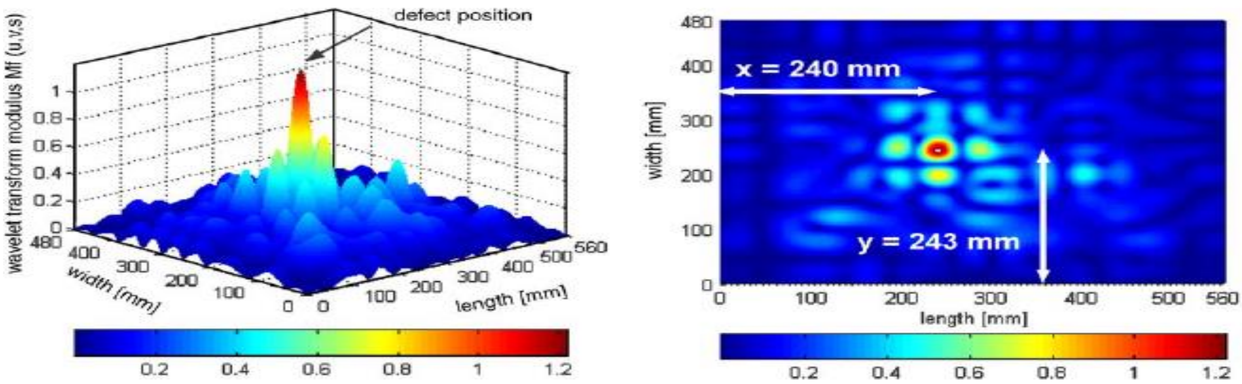


Figure 12 Wavelet coefficients and wavelet transform modulus for the plate using rbio5.5 wavelet based on experimental data (a) Isometric view b) Top view (Rucka and Wilde 2006)

Fig.11 & 12 shows rbio 5.5 wavelet damage detecting technique having high accuracy to locate and quantify the defect. The numerical values are very similar compare to the experimental data.

Reddy et al (2012) strain energy data is used for wavelet transform and show the effectiveness of the wavelet transform in the damage detection in plate structure. Mathematically, continuous wavelet transform, $wf_{a,b}$ of a f(x) is defined as

$$wf_{a,b} = 1/\sqrt{a} \int_{-\infty}^{\infty} f(x) \left(\frac{x-b}{a}\right) dx = \int_{-\infty}^{\infty} f(x)\varphi_{a,b}(x) \quad (2)$$

Whereas discrete wavelet transform $wf_{j,k}$,is defined

$$wf_{a,b} = 2^{\frac{j}{2}} \int_{-\infty}^{\infty} f(x)\varphi\left(2^j x - k\right) = \int_{-\infty}^{\infty} f(x)\varphi_{j,k}(x)dx \quad (3)$$

where a is the real-valued dilation parameter and b the real-valued translation parameter, φ is the mother wavelet ,j the integer dilation and integer translation index

Jaiswal and Pande (2015) shows the numerical studies for damage detection in beam structure with mode shape curvatures and its spatial wavelet transforms are discussed. Jaiswal and Pande (2016) compared the rotational and translational nodal displacement signals in damage detection in a beam structure with the help of different discrete wavelet transform and conclude higher mode shapes have better sensitivity in low level damage. Diaferio M and Sepe V (2016) Multi-span and multi-floor framed structures are considered and analyzed by means of a substructures approach, analyzing complicated structure experimentally is challenging and more sensors require.

7. CONCLUSIONS

This article provides a summary review on modal based damage detection for different types of structures. These methods are categorized as frequency based method, mode shape based method, mode shape curvature based method and wavelet based method. A review of vibration based crack detection technique exposed numerous and different algorithms, which utilised data in the time, frequency and modal domains. The literature demonstrates that there is no universal agreement as to the best method for using measured vibration data for damage detection, location or quantification. Particularly, the sensitivity and measurability of the modal parameter shifts due to localised damage so it leads to disagreement by the research community. So far proposed all type of damage detection algorithms are unable to predict the remaining life of a structure. In the same way there is no method which can be applied common to identify all type of damage in all type of structure. But some algorithms were capable of localize damage in only a single location, others were limited in the number of damage locations. Many algorithms assume access to a detailed FEM of the structure, while others assume that a data set from the undamaged structure is available. Frequently, the lack of availability of this type of data can make a method impractical for certain applications. In this study numerical methods are able to locate the defect but implementing the experimental test the results are poor because of its sensor position still it is challenging.

From frequency based damage detection method is able to find the defect which is present in the structure but it is not able to locate the defect. If the damage size is small this method is not applicable. Experimentally analysing this method is more challenging because of it sensor locating position. Mode shape based damage detection method overcomes the frequency based method. Mainly mode shape based and curvature based methods only focus on damage localization. The direct use of mode shape change can only roughly localize the damage. In order to make the damage detection algorithm effective some optimization algorithms or signal processing is necessary to increase the sensitivity of damage detection. Wavelet transform method is superior in damage detection even it is detect 5% of damage.

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