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ANALYSIS 2D WAVELET TRANSFORM TO IDENTIFY CRACK IN FUNCTIONALLY GRADED MATERIAL PLATES USING XFEM

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Keywords: *Wavelet analysis, crack identification, detection of crack, functionally graded material (FGM) plate, vibration mode, XFEM.*

ABSTRACT

Crack identification based on vibration analysis is an interestingsubject of intensive investigation in recent years. When a structure has a crack, the dynamic characteristics of the structure, such as natural frequencies and mode shapes, will be changed. An analysis of these changes will enable to identify cracks. In this paper, a method using 2D wavelet transformto detect the cracks in the functionally graded material (FGM) plate is introduced. The cracked FGM plate is modeled by the extended finite element method (XFEM)with discrete shear gap technique using triangular mesh (DSG3) to calculate the vibration mode. Themodal vibration data,which are the free flexural vibrations of cracked FGM plate,are then used as signal for wavelet analysis to determine the position of the crack. The numerical results show that the proposed method is not only accurate but also very visual.

1. Introduction

Functionally Graded Materials (FGMs) are often composed by two or more materials (such as metals and ceramics...) with the volume fractions changing continuously along certain direction of the structure. Combining the best properties of metal and ceramic components, FGMs are capable of resisting high temperature environments and extremely large temperature gradients. Therefore, FGMs become a potential material candidates for being used in aerospace structure applications, nuclear plants[14,16] and have being widely used in many other engineering areas such as civil, automotive, biomechanical, chemical and electronic industries.

Due toFGMs'great advantageous features in practical applications, many numerical methods have been used to compute, analysis and simulate the behaviors and dynamic characteristics of FGMs. Among these approaches, Finite Element Method (FEM) is one of the most powerful and reliable tools. Mesh-free methods and smoothed finite element methods (SFEM) [8]have been also developed recently and showed certain advantages in particular types of problems.

As in many other structures, an important issue cannot be neglected in analysis of FGM plates is fracture problem. FGM plates may develop flaws during manufacturing or after the amount of time working under cyclic loading. When a structure has a crack, the dynamic characteristics of the structure, such as natural frequencies and mode shapes, will be changed. This will strongly affect the working capability of plate.Hence it is important to compute and analyze the dynamic responses of a plate with crack inside[10]. To do this, one of first important tasks is to identify the crack location.There are many ways to detect crack in structures, one of the most powerful and effective tools is Wavelet analysis. Researches on using wavelet analysis for identification of damages in structures were published [1,2,4,11,12]and demonstrated the viability andeffectiveness of Wavelet in this particular area. However, applyingthe 2D wavelet analysis to identify cracks in FGM plates has not been reached yet.

In this paper, a method based on the two-dimensional discrete wavelet transform (2D DWT) of modal data to detectthe cracks in the FGM plates is introduced. The 2D DWT is much more complex than the 1D DWT, but the results obtained are very visual and impressive.

In practice, the modal vibration data which include the natural frequencies and mode shapes of cracked plate are usually defined by measured equipments. However, this usually leads to the measurement errors which much affect to the accuracy in measuring mode shapes. In order to avoid such measurement errors and focus mainly on studying the application ofthe 2D wavelet analysis in crack identification, the noisy vibration data generated by numerical methods are used. Specifically, the noisegenerated based on Box-Muller method is added to vibration data computed by numerical method to simulate experimental datain this paper. The numerical method used here is the extended finite element method (XFEM). The XFEM was first proposed in 1999 by T.Belytscko and Moes [13,17] based on the idea of partition of unity. Later then, many works on fracture mechanics using the XFEM have been developed and demonstrated the advantages of the XFEM in solving discontinous problems. John Dolbow *et al.* [7] showed how to model fracture in Mindlin-Reissner plates by the XFEM. In addition, one important issue of plate analysis which is shear-locking phenomenon was also given out in discussion. In this paper, the problem of shear-locking will be solved by the stabilized discrete shear gape technique using triangular mesh (DSG3)[3,9]. The DSG method has several superior properties and can be combined with the the adaptive technique to strongly improve the efficiency of themethod, but this point has not been performed in this paper.

Recently, the vibration of cracked FGM plates was also studied and published by S. Natarajan *et al.* [16] that contributed an important part to the study of FGMs and inspired us to perform this research.

This paper is organized as follows, the next section will present an introduction of FGM. In section 3, the XFEM with stabilizeddiscrete shear gap technique using triangular meshes is introduced briefly. In section 4, Wavelet analysis is also presented in brief with continuous and discontinuous transform. The algorithm for crack detection based on modal data analysis using 2D wavelet transform will be outlined in section 5. The numerical results are illustrated in section 6 with two cases of simply supported Al/Al_2O_3 and cantilevered square Al/ZrO_2FGM cracked platesand the last section will give out some conclusions and remarks on results obtained from the method proposed in this paper.

2. Formulation of Mindlin plates using functionally graded material

2.1 Functionally graded material

Functionally graded material (FGM) is composed by a mixture of two distinct material phases: ceramic and metal. Ceramic can resist high thermal load because its thermal conductivity is low while the metal component can maintain flexibility of structure under the high-temperature gradient.

The volume fractions of the ceramic and metal constituents are related by and expressed by [6]:

(1)

where z is the thickness coordinate which varies from *–t/2* to *t/2*; n is the volume fraction exponent which is also referred to as the gradient index. The variation of the volume fractions of ceramicsand metal in an FGM plate through the thickness direction is shown in Figure 1. When $n = 0$, the plate is fully ceramic, and when , the homogeneous metal plate is retrieved.

The effective mass density is given by the following relation

(2)

where the subscripts m and c refer to the metal and ceramic phases, respectively.

The effective material modulus of the ceramic and metal are computed from the formula [16]

(3)

where $P_c$and $P_m$denote the material properties (Young's modulus, Poisson ratio) of the ceramics and the metal.

The material properties P that are depended on temperature can be calculated as:

(4)

where are the coefficients of temperature T and are unique to each constituent material phase.

Figure 1. Variation of the volume fraction against the non-dimensional thickness.

2.2 Formulation of Mindlin plate [13]

The displacements at a point (x,y,z) in an FGM plate using the Mindlin-Ressiner theory are expressed as function of the mid-plane displacements u_o, v_o, $w_o$and independent rotations as follows [13]:

(5)

where t is the time. The strains in terms of mid-plane deformation can be written as

(6)

in which, , are respectively the mid-plane, bending, shearing strainsand defined as

(7)

where the subscript 'comma' represents the partial derivative with respect to the spatial coordinate succeeding it.

The membrane stress resultants **N** and the bending stress resultants **M** can be expressed as

(8)

where the matrices are the extensional, bending-extensional coupling and bending stiffness coefficients and defined as

(9)

The transverse shear force is defined in the similar way

(10)

where is the transverse shear stiffness coefficient, $v_x$and $v_y$are the transverse shear coefficients for non-uniform shear strain distribution through the plate thickness. The stiffness coefficients are defined as

(11)

where $E(z,T)$ is the modulus of elasticity and is the Poisson's ratio given by Eq.(3).

The strain energy function U is then expressed by

(12)

where is the vector of the degree of freedom associated to the displacement field.

The strain energy function can be rewritten in the following form

(13)

where **K** is the linear stiffness matrix. The kinetic energy of the plate is given by

(14)

where and is the mass density that varies through the thickness of the plate given by Eq.(2). Substituting Eqs. (13)and (14) into Lagrange's equations of motion, the following governing equation is obtained

(15)

where **M** is the consistent mass matrix.

From Eq.(16), we can lead out the eigen equation as follows

(16)

Where,is the natural frequency.

3. Brief on the eXtended FEM (XFEM) usingDSG3 [10, 14]

The extended finite element method (XFEM) was first proposed in 1999 by T.Belytschko, Black and Moes [13,17]. In this method, the mesh is independent and does not need to conform to the crack. This advantage helps to overcome the difficulties of remeshing of the standard FEM in solving problems related to crack, especially, crack propagation. In XFEM, enrichment functions are used to present the effect of crack and the field variables are then approximated by

(17)

where $N_i(x)$ are standard finite element shape functions, q_i are nodal variables associated with node i in which i is the node index and i = 1,2,3,4 for rectangular elements.

In Figure 2, the nodes marked with circle and square are being enriched with discontinuous and near-tip enrichment functions, respectively. The area between the enriched domain and the standard domain is called blending area, in which just some nodes of the element are enriched.

For the case of FGM plate, whose element has 5 degrees of freedom per node, the displacements and section rotations are as follows [13]:

(18)

(19)

where is the nodal enriched degree of freedom vector associated with the Heavisied functions and crack-tip functions, respectively.

Blending

Figure 2. Modelling crack with nodes enriched in the XFEM.

Tip Element

Vertex Element

Standard Elements

Split Element

G_k, F_k in the Eqs.(19), (20) are asymptotic functions expressed by

(20)

(21)

If we use the above interpolation functions to derive the shear strains and membrane strains directly, the element will be locked and show oscillations in the shear and membrane stresses. This phenomenon is usually referred to as shear-locking. The shear-locking has a large effect on the solution and significantly degrades the accuracy of the result.

To eliminate the shearlocking phenomenon, the discrete shear gap technique is usually used to modify the approximation of the section rotations in shear terms. The formulation of the DSG3 is based on the concept 'shear gap' of displacement along the sides of the elements. In the DSG3, the shear strain is linearly interpolated from the shear gaps of displacement by using the standard element shape functions. As a result, the entries of the matrix of shape function derivatives are constant and computed from the coordinates of node of elements. The section rotations in shear terms are then modified as follows:

(22)

[3,9,18]

where is the modified shape function, seefor more detail on DSG3 discussion.

The eigen equation for modal analysis using the XFEM with DSG3 mesh is then:

(23)

where the element stiffness matrix is given by:

(24)

where **D** is the material matrix, $\mathbf{B}_{std}$ and $\mathbf{B}_{enr}$ are the standard and enriched part of the strain-displacementmatrix, respectively. The element mass matrix is given by:

(25)

where is the effective mass density computed from (2). Note that, in deriving the element mass matrix (25), the plate displacements and the section rotations given by (18) and (22) are used.

4. Wavelet transform

4.1 Continuous Wavelet Transform

Wavelet analysis starts with selecting a basis function from Wavelet families. This function is called "Mother Wavelet" . The continuous wavelet transformation (CWT) is then defined as [1]

(26)

where and are scale and translation parameters. The result of CWT is wavelet coefficients $C(a,b)$ showing the correlations between the Wavelet function and the signal analysis.

4.2 Discrete Wavelet Transform

One drawback of the CWT is that a very large number of Wavelet coefficients $C(a,b)$ are generated during the analysis. In order to reduce the amount of computation, the Discrete Wavelet Transform (DWT) used discrete scale and translation parameters in dyadic form[4[11]]. The scale and translation are then defined as where , the is referred to as the dyadic level. And the DWT is as follows

(27)

The signal will be passed through a series of filters, the high-pass filters and low-pass filters, to generate high-frequency and low-frequency components, respectively.

Assuming that the wavelet coefficients are only valid for $a<a_0$, appropriate for high-frequency components in the signal. For $a>a_0$, seen as interference. In this case, the signal reconstruction needs the complement corresponding to $a>a_0$. To do this, another function called "scale function" is used.

The signal in DWT can be represented by approximations and details

(28)

where is the approximation at level J

is the detail at level .

and , are Detail coefficient and Approximation coefficient, respestively.

4.3 The 2D Wavelet transform

The choice for two-dimension scale function and wavelet function is usually a product of two one-dimensional functions. In 2D wavelet transform, three wavelet functions are usually used instead of one function as in 1D case. So, we have [15]

(29)

with (30)

Figure 3: Illustration of Decomposition process.

Note: Downsamples columns: keep the even indexed columns.

,

Downsample rows: keep the even indexed rows.

: Convolve with filter X the rows, columns of the entry

Note:

Upsample columns: Insert zeros at odd-indexed columns

Upsample rows: Insert zeros at odd-indexed rows

Figure 4: Illustration of Reconstruction step.

The scale and translation parameters are also discretized to decrease the computational cost. And the three wavelets can be written as [12]

(31)

The approximation and detail coefficients are then computed in a similar way as in 1D case.

The wavelet generates large coefficients along edges, which are horizontal and vertical respectively, while large coefficients are produced with at the corners or diagonal direction. The decomposition process can be illustrated as shown in Figure 3, and the reconstruction of Detail and Approximation parts of the signal is shown in Figure 4.

5. Algorithm for crack detection

To test the efficiency of the method for practical applications, experiments need to be carried out. However, due to the unavailability of the experimental data, in this paper, the noisy vibration modes generated by numerical methods are used instead. The noise generated based on Box-Muller method is added to vibration data computed by the XFEM to simulate experimental datain this paper. The noise added to the vibration modes are the Gaussian noise made from the following formular of the Box-Muller method [6]

(32)

where is the mean value, is the standard deviation and t,s are random variables belonging to the interval [0,1].

The algorithm for crack detection is performed in the following steps:

Modeling the cracked FGM plate using the XFEM. In this step, the discrete shear gap technique with triangularmesh are used to compute the stiffness matrix to eliminate the effect of shear locking phenomenon.

The mass matrix M and stiffness matrix K obtained from the first step are used for establishing eigen-value equation to compute modal parameters. The results obtained will be checked with Ref. [14[16] to ensure the accuracy.

The mode shapes herein are free flexural vibration modes, of the FGM plate with and without Gaussian noise added are used as input signal for wavelet analysis to compute detail and approximation coefficients.

Detail parts of the signal are then reconstructed and plotted in figure. The domain containing the crack will appear with very high values and easy to be determined visually.

6. Numerical results

In this section, we first compute the natural frequencies of acracked functionally graded material plate by using the extended finite element method meshing with DSG3 elements. Then, we apply the wavelet transform for the the first five mode shapes data to find out the location of the crack. The results will be tested for twocases of simply supported Al/Al_2O_3 and cantilevered square Al/ZrO_2 FGM cracked plates.

Consider an elastic square plate of thickness *t* with length *a* and width *b*containing a side crack of length *d* at the position $y_c$as shown in Figure 5.

The plates are made of Al/Al_2O_3 and Al/ZrO_2 with the material properties given in Table 1.

h

a

y_c

d

b

Figure 5. Simple supported plate with a side crack.

The natural frequencies and mode shapes are computed for both cases and compared with the results in Ref. [16] as listed in Tables 2 and 3. In all cases, we present the non-dimensional free flexural frequencies as

(33)

where are the Young's modulus and Poisson's ratio of the ceramic material, and is the mass density, respectively.

Table 1: Material properties of the FGM components

Material	Properties		
	E (GPa)		(Kg/m^3)
Aluminum (Al)	70.0	0.3	2702
Alumina (Al_2O_3)	380.0	0.3	3800
Zirconia (ZrO_2)	200.0	0.3	5700

Table 2: Comparison of non-dimensional natural frequency for a simply supported square Al/Al_2O_3 plate with a side crack (*a/b = 1, b/h = 10,* $y_c/a = 0.5$, *d/a = 0.5)*

	Mode I	Mode II	Mode III
Ref [13]	4.122	8.856	10.250
Present	4.137	8.038	10.698

Table 3: Comparison of non-dimensional natural frequency for cantilever Al/ZrO_2 plate with a side crack (*a/b = 1, b/h = 100,* $y_c/a = 0.5$, *d/a = 0.5)*

	Mode I	Mode II	Mode III
Ref [13]	0.9549	1.5970	4.4410
Present	0.9919	1.5973	4.2706

In this test, we just use a coarse mesh with the size of 24x24, but the above results agree with those in Ref. [16].The first mode shapes for both cases are plotted in Figures6 and 7.As we can see, it is really hard to identify the presence of the crack by observing the figures of mode shapes. We need to use a special technique, *Wavelet transform*, to detect the positions having discontinuous values in modal data field.

x

z

Figure 6. The first mode shape of the simply supported Al/Al_2O_3 FGM cracked plate.

Figure 7. The first mode shape of the cantilever Al/ZrO_2 FGM cracked plate.

z

x

The two-dimensional data built from eigen-vector field (free flexural vibration modes) with and without Gaussian noise are then used as input signal for wavelet analysis. In the paper, the two-dimensional discrete wavelet transform will be chosen to analyze the data.

For the analysis, we use level one of decomposition because it provides coefficients of finest detail. The horizontal detail is sensitive to the defects in the orientation parallel to the x axis and therefore, the location of the crack will be detected based on identifying the position of large detail magnitude on wavelet diagram (Figure 8).

The vertical detail is sensitive to defects in the orientation parallel to the y axis and the diagonal detail is not sensitive to defects in the orientation parallel to the x and y axis and hence the diagonal detail coefficients are of low value [15].

Figure 8 and Figure 9 illustrate the estimate for the first modes of vibration without Gaussian noise for both cases of square and rectangular plates. In these figures, the highest values of detail coefficients appeared exactly and visually at the position of the crack.

To test the efficiency and the accuracy of the method, the Gaussian noise generated by Box-Muller method is added to the modal vibration data to simulate the experimental data. In this paper, the noisy data field is generated based on the formula (32) as follows: the mean value is set by “the value of mode shape at each node, z_i”. The standard deviation is expressed through the term of , where is referred to as the density of noise. The variation of can make the noise stronger or weaker. In this test, we chose (1% of the nodal value). The formula(32) can be expressed as:

(34)

where is the value of mode shape at node i with noise added. By this way, the noisy data field is formed.

x

z

Figure 8. Wavelet analysis with level one of decomposition for square plate case.

Figure 9. Wavelet analysis with level one of decomposition for Al/ZrO_2 plate case.

z

Figure 10. Noisy vibration mode generated by Box-Muller Method for the case of simply supported Al/Al_2O_3 FGM cracked plate

z

x

Figure 11. Result of the 2D wavelet analysis for the case of noisy vibration mode case.

z

x

These noisy data are then used as input signal for wavelet analysis process. The vibration mode with Gaussian noise is illustrated in Figure 10. The result of using wavelet to analyze noisy modal data is depicted in Figure 11.

From the result shown in Figure 11, it is clear that when the noise is added to modal data, the Detail diagram is also influenced. The disturbance appears almost everywhere corresponding to the present of the noise in the mode-shape data. However, the highest values of detail coefficients only appear along the crack line with dominant amplitude. This helps us to identify the area in which the crack located.

The above result demonstrated the efficiency of the proposed method in detection of crack. The accuracy of wavelet analysis is not much influenced by noise. This states that the proposed method is quite applicable and reliable in practice.

7. Conclusions

In this paper, a method based on the wavelet analysis of modal vibration data is introduced to detect the cracks in the functionally graded material (FGM) plate. In practice, the modal vibration data are usually defined by measured equipments which leads to the the measurement errors. And in order to avoid such the measurement error and focus mainly on studying the effectiveness of the 2D wavelet analysis in identification of crack, the numerical analysis with noisy data is used to simulate the experimental data in this paper. The numerical analysis used here is the extended finite element method (XFEM) with DSG3 mesh which can compute the free flexural vibrations of cracked FGM plates.The results of modal dataobtained show good accuracy in comparison with those of references.The errors are acceptable even with coarse mesh. The noisy modal data are then used for wavelet analysis process to locate the position of the crack. The test result demonstrated the applicability and reliability of the proposed method in practice. A simple algorithm for detection of crack based on analysis the vibration modes of a cracked plate using thetwo-dimensional wavelet transform was presented and the reliability of the method was demonstrated by the accuracy and visualization of the crack location determined.

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