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Damage Detection in Single Tapered Rectangular Cross Section Cantilever Beam using Neural Networks based on Vibration Characteristics

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Abstract: ***This paper proposes the use of Artificial Neural Networks (ANN) for the detection of crack location and crack depth in wind turbine blades. Wind turbine blade is approximated by a laminated composite, cantilever tapered beam with a transverse open surface crack. Experimental results are taken from literature to validate the results obtained from the finite element software ANSYS. The numerical data obtained from (FEM) are then used to train a feed-forward back propagation neural network using Matlab. The simulation results show that the proposed Neural Network can precisely detect the crack location and crack depth.***

Keywords: cantilever beam, neural networks, vibration, ANSYS

1. Introduction

The basic idea behind this technology is based on the fact that a crack in a structure induces local flexibility which affects the dynamic behaviour of the whole structure to a considerable degree. The input parameters to the neural network are the first three relative natural frequencies, while the output parameters are the relative crack depth and relative crack location. The actual data are obtained using Finite Element Method via ANSYS software for different crack location and depth. The finite element modeling of the cracked laminated composite beam is simulated with an eight node linear layered 3D shell element with six degrees of freedom at each node (specified as shell181 element in ANSYS).

Since each fabric layer corresponds to 2 different fiber orientation (fibers at 0 o and 90o), two different layers were used to simulate each ply. The finite element analysis using ANSYS software was used in modal analysis to obtain the natural frequencies.

2. Literature Survey

Crack localization and sizing in a beam from the free and forced response measurements method is indicated by Karthikeyan et al. [1]. In the beam Timoshenko beam theory is used for modelling transverse vibrations.FEM is used for the free and forced vibration analysis of the cracked beam and open transverse crack is selected for the crack model. Being iterative in nature the iteration starts with a guess for the crack depth ratio and iteratively estimates the crack location and crack depth until the desired convergence for both is reached. The amount of literature related to damage detection using shifts in resonant frequencies is quite large. Salawu and Williams [2] presents an excellent review on the use of modal frequency changes for damage diagnostics. The observation that changes in structural properties cause changes in vibration frequencies was the impetus for using modal methods for damage identification and health monitoring Kim and Zhao [3] proposed a novel crack detection method using harmonic response. It was concluded in their paper that slope response has a sharp change with the crack location and depth of the crack and therefore it can used as a crack detection criterion. A fault diagnosis method based on genetic algorithms (GAs) and a model of damaged (cracked) structure is proposed by Taghi et al. [4]. In their approach the identification of the crack location and depth in the cantilever beam is formulated as an optimization problem, and binary and continuous genetic algorithms (BGA, CGA) are used to find the optimal location and depth by minimizing the cost function. Ratcliffe [5] performed the frequency and curvature based experiments. Orhan [6] in his study analyzed the free and forced vibration of a cantilever beam in order to identify the crack of a cantilever beam. Single and two edged crack were mainly evaluated in his study. The investigation reveals that free vibration analysis provides suitable information for the detection of single and two cracks; whereas forced vibration can detect only the single crack condition.

3. Theory

The stability and local flexibility of the beam depends on the material properties, physical dimensions, boundary conditions of the structure. The characteristics of beam greatly depend on the position of crack, depth of crack orentiation of crack and number of cracks. The beam with rectangular crack clamped at one end and free at other endand tapered width cross section and uniform thickness. The crack is assumed to be open crackand no damping is considered.

$$\omega_n = C * \sqrt{\frac{EI}{\rho A L 4}}$$

$$I = \frac{bd3}{12}$$

C1= 0.56 for first mode
C2= 3.52 for second mode
C3= 9.82 for third mode

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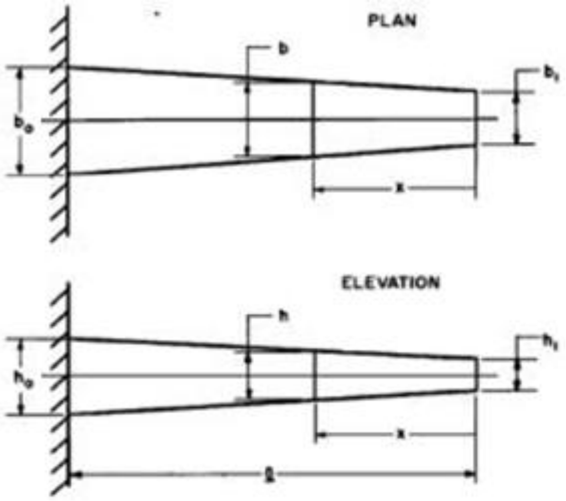

Figure 1: Two views of tapered cantilever beam

Stiffness matrix (I0 and I1 are area moment of inertia at big end and small end)
Mass matrix (having A0 and A1 are areas at big end and small end respectively)
b0= width of beam at base end and b1= width of beam at small end.

I0=$\frac{b0h03}{12}$

I1=$\frac{b1h13}{12}$

A0=b0h0

A1=b1h1

$$[K^e]=E\begin{bmatrix} \frac{6(I_0+I_1)}{l^3} & \frac{2(I_0+2I_1)}{l^2} & -\frac{6(I_0+I_1)}{l^3} & \frac{2(2I_0+I_1)}{l^2} \\ \frac{2(I_0+2I_1)}{l^2} & \frac{I_0+3I_1}{l} & -\frac{2(I_0+2I_1)}{l^2} & \frac{I_0+I_1}{l} \\ -\frac{6(I_0+I_1)}{l^3} & -\frac{2(I_0+2I_1)}{l^2} & \frac{6(I_0+I_1)}{l^3} & \frac{2(2I_0+I_1)}{l^2} \\ \frac{2(2I_0+I_1)}{l^2} & \frac{I_0+I_1}{l} & -\frac{2(2I_0+I_1)}{l^2} & \frac{3I_0+I_1}{l} \end{bmatrix}$$

$$[M^e]=\rho\begin{bmatrix} \frac{l(10A_1+3A_0)}{35} & \frac{l^2(15A_1+7A_0)}{420} & \frac{9l(A_1+A_0)}{140} & -\frac{l^2(7A_1+6A_0)}{420} \\ \frac{l^2(15A_1+7A_0)}{420} & \frac{l^3(3A_1+5A_0)}{840} & \frac{l^2(6A_0+7A_1)}{420} & -\frac{l^3(A_0+A_1)}{280} \\ \frac{9l(A_0+A_1)}{140} & \frac{l^2(6A_0+7A_1)}{420} & \frac{l(10A_0+3A_1)}{35} & -\frac{l^2(15A_0+7A_1)}{420} \\ -\frac{l^2(6A_0+7A_1)}{420} & -\frac{l^3(A_0+A_1)}{280} & -\frac{l^2(15A_0+7A_1)}{420} & \frac{l^3(5A_0+3A_1)}{840} \end{bmatrix}$$

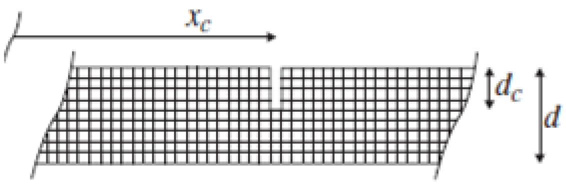

Figure 2: Crack notations

As shown in Fig:2 xc is location of crack from fixed end of cantilever beam, dc is depth of crack and d is the total depth of beam.

Neural networks

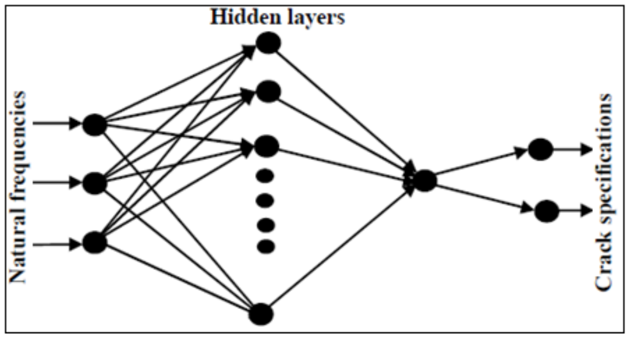

Figure 4: Schematic diagram of the ANN.

In this work, the first three relative natural frequencies are employed to predict the crack location and crack depth of the composite tapered beam. The first three relative natural frequencies of the composite tapered beam are chosen as inputs, while the relative crack location and crack depth (a) are chosen tobe outputs. Thus three inputs –two outputs neural network is used. A feed forward back propagation neural network has been used in Matlab software. Tan-sigmoid functions were used in all hidden layers and pure linear function in output layers. Levenberg-Marquardt algorithm is employed to train the network using the 'trainlm' function.

Flow diagram for nueral network

Create network object and initiate it
Use command newff

Train the network
Use command Train

Test the network
Use command sim

4. Methodology

Using the above stiffness and mass matrices natural frequencies are theoritically calculated with the help of matlab software. These frequencies are used for verifying the ANSYS generated frequencies. And the ANSYS generated frequencies are used as input for training the nueral network. Finally the nueral network is tested by giving frequency to know the crack location and depth.

5. Results

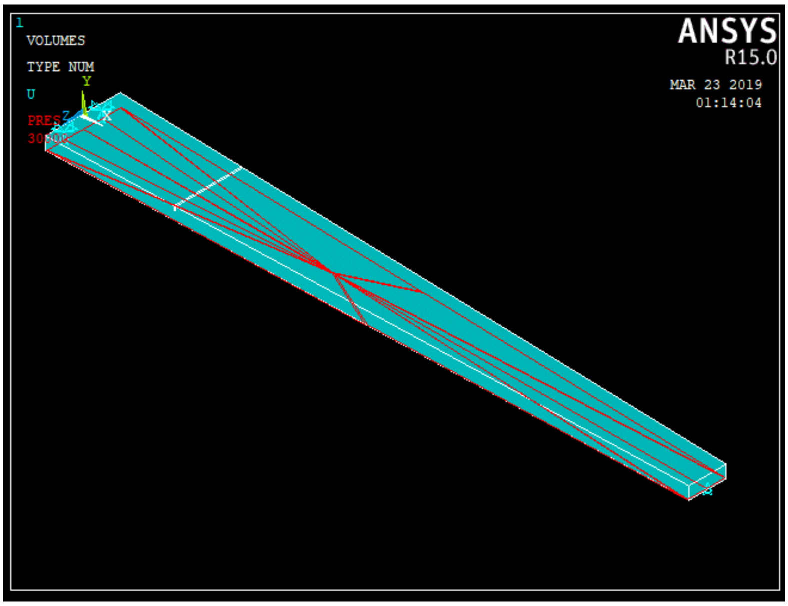

Figure 3: ANSYS model tapered cantilever beam with loading and boundary conditions

Ansys modelling is done using shell 181 element with dimensions and material properties. Refinement level 3 is taken for meshing.

w1(width at small end in mm)	30
w2(width at big end in mm)	60
L(mm)	500
Thickness(mm)	10
E(GPa)	69
Poissons's ratio	0.33
Density(Kg/m^3)	2700

Crack is created at different positions with different depths and model frequencies are tabulated. And this data is used for training the neural network.

Test data

Sample N0	Crack location	Crack depth	f1	f2	f3		
1	40	1	29.983	165.06	443.35		
4	100	1	29.925	166.36	439.99		
7	180	1	31.154	170.91	455.62		
10	260	1	30.684	165.35	446.72	file:text(13).pdf	
11	280	1	30.94	170.29	456.23		
17	420	1	30.697	168.52	449.96	w1	30
21	20	2	29.736	163.85	439.43	w2	60
23	80	2	29.187	158.19	426.46	L	500
35	380	2	30.596	166.97	443.5	thickness	10
39	460	2	30.708	165.05	438.98		
55	380	3	30.593	166.79	442.22		
64	100	4	29.581	166.33	439.05		
89	220	5	30.354	161.59	439.4		
95	360	5	30.596	165.24	431.5		
107	160	6	30.037	168.38	436.6		
113	300	6	30.686	163.05	443.6		
119	460	6	30.636	164.71	438.17		
121	0	0	31.986	173.66	459.64		

6. Conclusion

The stiffness of a cracked beam is lower than the stiffness of an un-cracked beam and that condition is reflected in the reduction of the natural frequencies of the cracked beam in its free dynamic response. The trained neural network is able to detect the location and depth of crack for the fed natural frequency. When depth is 3mm neural network is predicting frequency as 31.154 Hz while for the same depth ANSYS calculated frequency is 30.593 Hz.

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Appendix-A

Matlab program for first natural frequency without crack for tapered cantilevered beam

```
% L : length of the beam
% b : width of a rectangular beam
% h : thickness ofthe beam
% constant to be declared
rho = 2.77e+03;
E = 70e+09;
L = 0.762;
h = 0.0254;
b0 = 5.715e-02;
b1 = 3.51e-02;
I0=b0*h^3/12;
I1=b1*h^3/12;
A0=b0*h;
A1=b1*h;
KT=E*[6*(I0+I1)/L^3 2*(I0+2*I1)/L^2 -6*(I0+I1)/L^3
2*(2*I0+I1)/L^2 ;
2*(I0+2*I1)/L^2 (I0+3*I1)/L  -2*(I0+2*I1)/L^2 (I0+I1)/L;
-6*(I0+I1)/L^3 -2*(I0+2*I1)/L^2 6*(I0+I1)/L^3 -
2*(2*I0+I1)/L^2;
2*(I0+2*I1)/L^2 (I0+I1)/L -2*(2*I0+I1)/L^2 (3*I0+I1)/L];

MT=rho*[L*(10*A1+3*A0)/35 L^2*(15*A1+7*A0)/420
L*(A1+A0)/140 -L^2*(7*A1+6*A0)/420 ;
L^2*(15*A1+7*A0)/420 L^3*(3*A1+5*A0)/840
L^2*(A1+6*A0)/420 -L^2*(A1+A0)/280;
L*(A1+A0)/140 L^2*(A1+6*A0)/420 L*(3*A1+10*A0)/35
-L^2*(7*A1+15*A0)/420;
-L^2*(7*A1+6*A0)/420 -L^2*(A1+A0)/280 -
L^2*(7*A1+15*A0)/420 L^3*(3*A1+5*A0)/840];
Lamda=eig(KT-MT)
omegan=sqrt(lamda)/2*pi %cycles per
second
%answer
% 820.43 cycles per second
% 168.11 cycles per second
%  54.45 cycles per second
```

Appendix-B

Neural network Program in MATLAB

```
%crack size
a1=0:1:6;
%a2=0.0003:0.0003:0.003;
%crack location
L1=[40 100 180 260 280 420  20  80  380 460 380 100 220
360 160 300 460 0];

%L2=0.08:0.04:0.72;
%target
x=[a1 L1];
%input (transpose of a1)
f1=[29.983  29.925  31.154  30.684  30.94   30.697  29.736
29.187  30.596...
   30.708  30.593  29.581  30.354  30.596  30.037  30.686
30.636  31.986 ...
   30.857  30.85   30.787  30.747  30.733  30.716  31.986
];
%initiation
net=newff(minmax(a1),[13 1],{'logsig','purelin','trainln'});
%specifications
net.trainparam.epochs=100;
net.trainparam.goal=1e-25;
net.trainparam.lr=0.01;
%training
net=train(net,x,f1);
%testing
x=sim(net,a1(3))
%answer is 31.154
```