Dynamic Analysis of a Structural Beam with Surface Crack Using Artificial Neural Network

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Abstract- The presence of microstructural defects such as cracks is known to have resulted in catastrophic failures. These failures lead to enormous loss of resources including human lives. To help prevent such losses, the scientific community has been studying the mechanics of crack propagation and trying to develop methods for early detection of cracks. Out of the various alternative techniques being explored, study of the impact of crack presence on the flexibility and vibration response of the structural or machine elements has gained popularity in past few decades. It is based on the theory, supported by observations, that the presence of crack in any structure/machine element alters its dynamic response and thus, this change in the response can be used as an indicator to predict presence of cracks.

In order to have an insight into the effects of crack on the response parameters, one has to carry out several repeated simulations. Various analytical and numerical methods have been applied by researchers working in this direction. But the usual approach adopted is very tedious and time consuming. In this paper, the authors have applied artificial neural network to a vibration analysis problem of a cantilever beam with surface crack using Finite Element Method (FEM) formulation. The results show that Artificial Neural Network (ANN) helps to reduce the efforts involved in simulations while providing solutions with fairly reasonable accuracy.

Index Terms— Artificial neural network, Surface crack, Finite element method, Fracture mechanics, Cracked beam, Dynamic response, Modal analysis, Cracked beam element.

1 Introduction

In the design of machineries and structures, there is an increase in the importance associated with optimizing multiple objectives such as maximum life and strength, minimum weight and cost, etc. This makes them subjected to high level of fatigue stresses, resulting in the formation of cracks in their elements. Moreover various structural flaws such as notches, slits, irregular change in geometry of beams and micro-cracking are inhibited in the structure due to fatigue. The existence of such flaws in the structures and machineries in arduous conditions may lead to catastrophic failures [1]. A vast collection of case studies related to premature failures resulting from fatigue cracks is available in literature [2], [3]. Therefore it is imperative for the timely detection of cracks so that corrective action can be taken well before it grows critical [4].

For understanding the underlying relationship between the crack parameters and their effects on modal behavior of the structure, finite element analysis is carried out for several combinations of crack depth and crack location in the structure. Many researchers have carried out vibration analysis of cracked structures using Finite Element formulation and other analytical and numerical methods [4], [5], [6], [7], [8], [9], [10], [11] and [12]. Research in the past few decades on cracked structures is well documented by Dimarogonas [13] and is quoted in most of the papers related to the field.

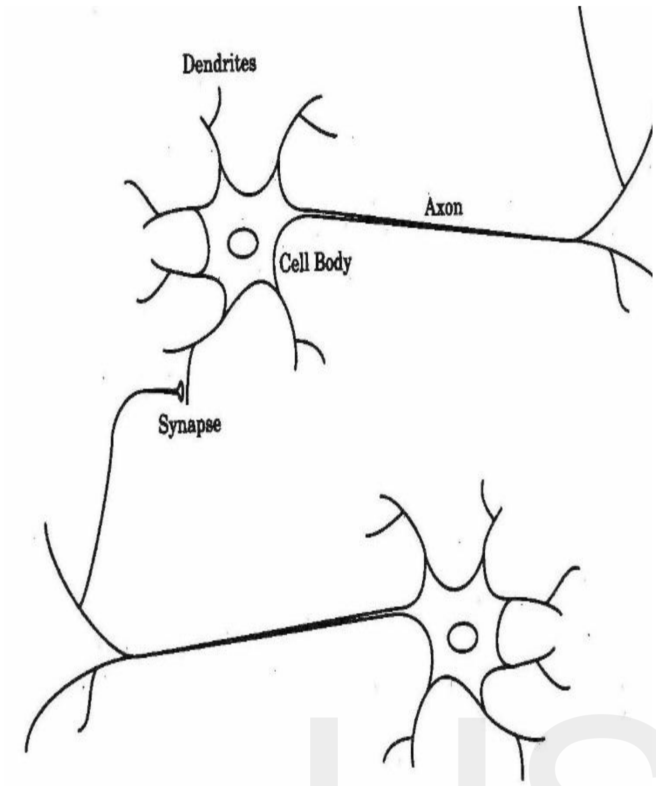
Thus it calls for the application of some intelligent techniques which will help in reducing the efforts. One of the techniques known as Artificial Neural Network (ANN) can help to create a black – box approach for the problem. ANN basically is a computational technique that has the ability to model relationships between the process variables, given sufficient number of values for the input and the corresponding output values [14]. In the subsequent sections, ANN is briefly explained and its application in the vibration analysis of a cracked beam is discussed.

2 Artificial Neural Network (ANN)

An artificial neural network (ANN), usually called neural network (NN), is a biologically inspired approach to machine learning where the mathematical model of a process is developed empirically rather than using mass and energy transport equations [14]. These models are relatively crude electronic models which mimic the real life behavior of neurons present in the brain [15] as shown in figure 1. It consists of formal neurons connected with each other such that each neuron output further serves as the input of generally more neurons in the same way as the axon terminals of a biological neuron are connected with dendrites of other neurons. Certain problems that are beyond the scope of current computers are indeed solvable by small energy efficient packages [15], hence this new technique for computation also provides a more graceful degradation during overload of the system than its more traditional counterparts.

During the learning phase, according to the external or internal information that flows through the network artificial neural network adapts itself. They are usually trained to model complex underlying relationships between inputs and outputs as well as to find patterns in data as shown in figure 2.

Fig. 1: Biological Neural Network



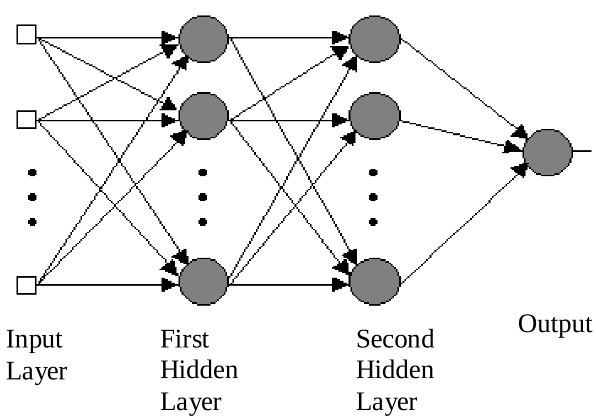


Fig. 2: Artificial Neural Network

3 Mathematical Representation Of ANN

The mathematical model of an artificial neural network is obtained by reformulating the function of a biological neuron into a mathematical expression and is shown in figure 3. It consists of four parts which are input neurons in the input layer, a computational unit, weighting factors and an activation function. Referring to Figure 3, the signal flow from inputs $x_1, x_2, x_3 \ldots x_n$ is considered to be unidirectional, which are indicated by arrows, comes from the dendrites. The inputs are associated with their corresponding synaptic weights w_1, w_2, $w_3 \ldots w_n$ which are a measure of their permeability. Therefore, the weighted sum of input values represents the excitation level of the neuron: The neuron output signal *O* is given by the following relationship:

$$O = f(\xi) = f(\textstyle\sum_{i=1}^{n} w_i x_i) \qquad (1)$$

where, w_i are the associated synaptic weights, xi are the inputs and ξ is the excitation level of a neuron which is defined as the scalar product of weights and the input vectors.

$$\xi = w^T x = w_1 x_1 + \cdots + w_n x_n \qquad (2)$$

Where, $w^T$is the transpose of the weight matrix.

Once the value of excitation level ξ reaches the threshold value h, it induces an output O which models the electric impulse generated by axon and the non-linear grow of output value O = f(ξ) is determined by the activation function f. The simplest type of activation function is of the following form:

$$O = f(\xi) = 1 \text{ if } \xi > h \qquad (3)$$

$$O = f(\xi) = 0 \text{ if } \xi < h \qquad (4)$$

This type of node is known as the linear threshold unit.

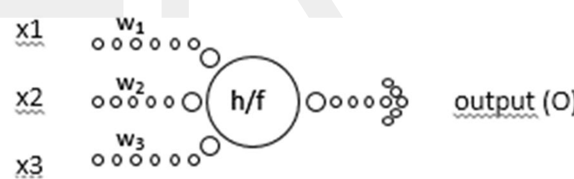


Fig. 3: Mathematical Model of ANN

4 Topologies Of Neural Networks

The basic neural network architecture consists of three types of neuron layers: input, hidden, and output layers as shown in figure 2. The data can be propagated in between these layers in 2 different ways using feed-forward neural network and recurrent neural network.

In feed-forward networks, the signal flows from input to output units, strictly in one direction. There are no cycles or loops. Propagation of data extends over multiple units, but no feedback connections are there as compared to recurrent networks which contain the feedback connections. Recurrent neural networks (RNN) can be used as general sequence processors. Certain cases deal with the activation values of the units which go through a relaxation process to stabilise the network. In other cases where significant changes in the activation values of the output neurons are observed, the dynamical behaviour constitutes the output of the network.

Apart from these two, few other types of neural network architectures (Competitive networks, Elman network, Adaptive resonance theory maps, etc.) are also used, depending on the type of the application. An overview of the different neural network architectures and learning algorithms was reported by Bishop [16].

A neural network is configured in such a way to as meet a set of outcomes using certain input values. Numerous techniques are there to set the strengths of the connections. Weights can be set explicitly with the help of a priori knowledge or a neural network can be trained by feeding it teaching patterns which in turn varies its weights according to the learning rule. Supervised learning, unsupervised learning, and reinforcement learning are the three learning situations in neural networks.

In supervised learning, at the inputs, an input vector is presented together with a set of desired responses, one for each node, at the output layer. After initiating a forward pass, the errors between the desired and actual response for each node in the output layer is determined which is then utilised to set the weight changes.

Unsupervised learning deals with the training of the units to respond to clusters of pattern within the input. In this learning condition, statistically recognizes the features of the input population. Contrary to the supervised learning paradigm, instead of having a priori set of categories for the classification of patterns, the system is concerned with the self-development of the representation of the input stimuli. Reinforcement learning deals with optimising a numerical award signal. In this learning situation, the learner must discover which actions give the optimised reward by trying them. Characteristics: trial-error search and delayed reward are the two salient features of reinforcement learning.

5 Neural Networks Training

The method of ascribing the attributes for the weights enables the training process. Training of the network can be defined as the process where the weights are modified while establishing connections between network layers with the target of approaching the true output [17]. When a network is trained, an internal process takes place which is called learning. A neural network is trained using trial and error method. Weights of a random link are adjusted so as to improve the behavior of the neutral network. While adjusting the weights if the accuracy of the neural network tends to decline, undo the change and make a different one. Various algorithms have been defined for training purpose namely: Back propagation Algorithm, The simple neuron - the Single Layer Perception, The Multilayer Perception. Back-Propagation Algorithm is a widely used algorithm which works on supervised learning. In this the algorithm is provided with a set of data we want to solve and on the basis of error (difference between actual and expected values), solution is obtained.

The crux of the problem is to minimize this error, until the ANN learns the training data. Initially the training begins with random weights and is pursued further by changing the random weights so that the error is minimized and optimal solution is reached.

6 Dynamic Analysis Cantilever Beam With Crack Using ANN

As discussed earlier, the common approach adopted to determine linear response of cracked beams is based on combination of fracture mechanics and finite element method, which is successfully applied to the problem by various researchers [4], [5], [6], [7], [8], [9], [10], [11] and [12].

This calls for several simulations of the same problem with varied crack depths and locations along the beam length, making it a time consuming affair. The prime objective of this work is to reduce the efforts using ANN.

The beam selected for this problem is the one used by one of the authors in his previous works [18], where ANSYS was used for FEA of cracked beam.

The dimensions of the cantilever beam analyzed is 300mm x 20mm x 20mm with material properties-E=206.8GPa, Poisson's ratio=0.3 and density =7853kg/m^3. This beam has been analyzed by Ismail [18] using ANSYS, to determine its natural frequencies for different values of the crack parameters 'a/s' and 'h/l'.

Where,

a - Crack depth (mm)

s- Beam height (mm)

h - Distance of crack from fixed end of the beam (mm)

l- Length of the cantilever beam (mm)

Input and results from [18] have been used as training data for our ANN. A 3-layer neural network model is used. The ANN has 2 neurons in the input layer for normalized crack depth (a/s) and normalized crack location (h/l). The hidden layer has 13 neurons, this determined found by trial and error. 80 input-output readings were taken from [9], out of which 70 were used for training and some values were excluded from training, to be used as test data. The network was programmed in MATLAB is a feed forward network. The Back-Propagation Algorithm was used to train the network.

7 Results

After training the network was provided with test values of crack parameters (a/s and h/l) and first three natural frequencies were obtained. Figures (4-6) below show that the values of natural frequencies obtained by the developed ANN are in good agreement with those obtained using FEM.

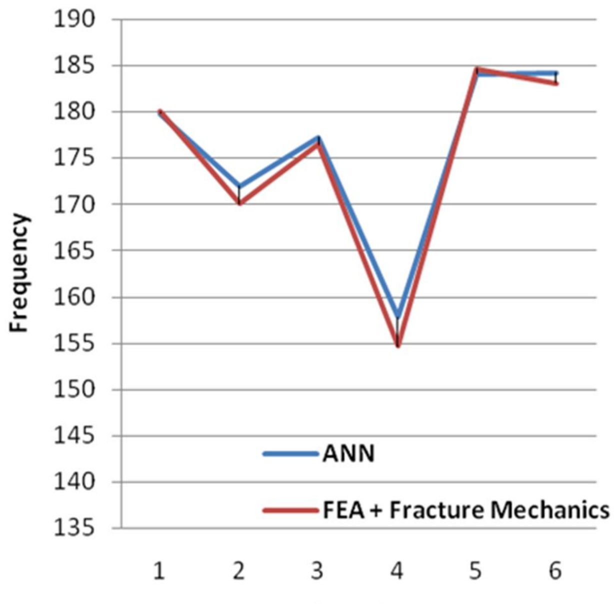


Fig. 4: 1st frequency results by ANN and FEM

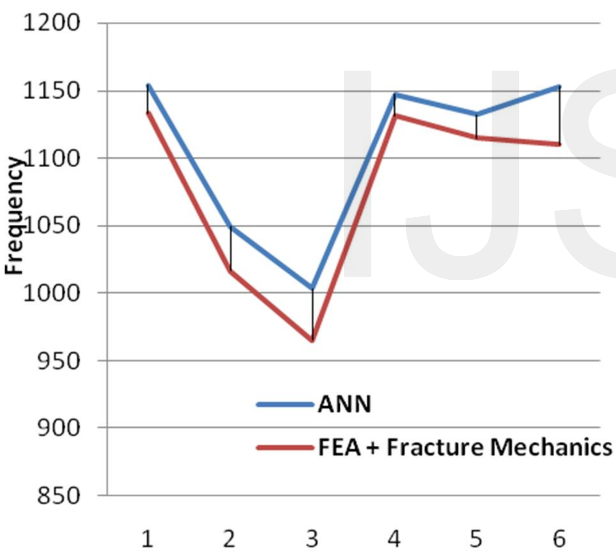


Fig. 5: 2nd Frequency Results by ANN and FEM

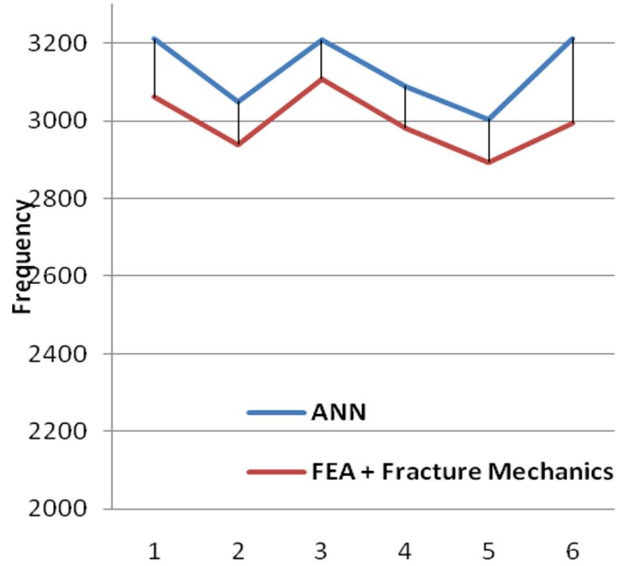


Fig. 6: 3rd Frequency Results by ANN and FEM

8 CONCLUSION

It can be observed in fig.4, fig. 5 and fig. 6 that presence of crack changes the natural frequencies of the beam. The frequency of a cracked beam tends to decrease as compared to an un-cracked beam. Also the effect of crack on these frequencies is dependent on the location and depth of the crack. Furthermore, by applying ANN in this case, the need to remodel the beam over and again for different crack parameters and re-run the FE Analysis is eliminated. Instead of that we can simulate the beam for a few trials to get enough data for training the neural network and then rest of the desired output values can be obtained from the Neural Network itself.

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REFERENCES

[1] S.D. Tawale and R.V. Patil. “Diagnosis for Structural Health of Rotor Dynamic Systems: A Review”, International Journal of Innovative Research in Science, Engineering and Technology, vol. 3, Issue 2, February 2014.
[2] F. Ellyin, *Fatigue Damage, Crack Growth and Life Prediction*, Chapman & Hall, London, 1997.
[3] S. Suresh, *Fatigue of Materials*, Cambridge University Press, Cambridge, 1991.
[4] M. Karthikeyan, R. Tiwari and S. Talukdar, “Crack localization and sizing in a beam based on the free and forced response measurements, Mechanical Systems and Signal Processing”, vol. 21, pp. 1362-1385, 2007.
[5] H. Nahvi and M. Jabbari, “Crack detection in beams using experimental modal data and finite element model”, International Journal of Mechanical Sciences, vol. 47, pp.1477–1497, 2005.
[6] C.C. Athanasios and A.P. Chris, “Identification of multiple

cracks in beams under bending", Mechanical Systems and Signal Processing, vol. 20, pp. 1631-1673, 2006.
[7] D.P. Patil and S.K. Maiti, "Experimental verification of a method of detection of multiple cracks in beams based on frequency measurements", Journal of Sound and Vibration, vol. 281, pp.439–451, 2005.
[8] R. Ruotolo, C. Surace, P. Crespo and D. Storer, "Harmonic analysis of the vibrations of a cantilevered beam with a closing crack", Computers and Structures, vol. 61, no. 6, pp.1057–1074, 1996.
[9] N. Dharmaraju, R. Tiwari and S. Talukdar, "Identification of an open crack model in a beam based on force–response measurements", Computers and Structures, vol. 82, pp.167–179, 2004.
[10] K. Murat and G.M. Arif, "Free vibration analysis of uniform and stepped cracked beams with circular cross sections", International Journal of Engineering Science, vol. 45, pp.364–380, 2007.
[11] B.P. Nandwana and S.K. Maiti, "Detection of the location and size of a crack in stepped cantilever beams based on measurements of natural frequencies", Journal of Sound and Vibration, vol. 203, no. 3, pp. 435-446, 1997.
[12] S. Chinchalkar, "Determination of Crack location in beams using natural frequencies", Journal of Sound and Vibration, vol. 247, no. 3, pp. 417-429, 2001.
[13] A.D. Dimarogonas, "Vibration of cracked structures: a state of the art review", Engineering Fracture Mechanics, vol. 55, no. 5, pp. 831-857, 1996.
[14] E.A.-Medina, J.I.P.-Paredes, "Artificial neural network modelling techniques applied to the hydro-desulfurization process", Mathematical and Computer Modelling, vol. 49, Issues 1–2, pp. 207–214, January 2009.
[15] S.B. Maind, P. Wankar, "Research Paper on Basic of Artificial Neural Network‖, International Journal on Recent and Innovation Trends in Computing and Communication", vol. 2, Issue: 1, January 2014.
[16] C.M. Bishop, *Neural Networks for Pattern Recognition*, Oxford University Press, Oxford, UK, 1995.
[17] S.N. Sivanandam, S.N. Deepa, *Introduction to Neural Networks Using MATLAB 6.0*, Tata McGraw-Hill Education, 2006.
[18] Ismail Akbani, "Crack Detection in Beams Using Vibration Analysis", M.Tech. Thesis, Visvesvaraya National Institute of Technology, Nagpur, India, 2010.