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ANN-Based Crack Identification in Rotor System with Multi-Crack in Shaft

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Abstract. Rotating machinery, such as steam turbo, compressor, and aeroengine etc., are widely used in many industrial fields. Among the important rotor faults, the fatigue crack fault, which can lead to catastrophic failure and cause injuries and severe damage to machinery if undetected in its early stages, is most difficult to detect efficiently with traditional methods. In the paper, based on the truth of the change of the mode shapes of the cracked structure, a new method by combining accurate finite element model of rotor with multi-crack in shaft and artificial neural network (ANN) is proposed to identify the location and depth of cracks in rotating machinery. First, based on fracture mechanics and the energy principle of Paris, the accurate FE model of the rotor system considering several localized on-edge non-propagating open cracks with different depth, is built to produce the specific mode shapes. Then a set of different mode shapes of a rotor system with localized cracks in several different positions and depths, which will be treated as the input of the designed ANN model, can be obtained by repeating the above step. At last, with several selected crack cases, the errors between the results obtained by using the trained ANN model and FEM ones are compared and illustrated. Meanwhile, the influences of crack in the different position on the identification success are analyzed. The method is validated on the test-rig and proved to have good effectiveness in identification process.

Introduction

The fault identification and diagnosis of rotating machinery, i.e. rotor system, have become a vigorous area of work during past decade [1]. Although the dynamic behaviors of rotor with single transverse crack have been studied relatively enough[2,3,4] and many methods have been introduced to detect it, the study of multi-crack case is not sufficient, especially for the multi-crack in rotating machinery.

In the paper, a new method, as shown in Fig. 1, by combining accurate FE (Finite Element) model of rotor with transverse cracks and artificial neural network (ANN) is proposed to identify the location and depth of cracks in rotating machinery. Initially the accurate FE model of the object, a rotor system with localized transverse on-edge non-propagating open cracks, is built to produce the specific mode shapes. Then a set of different mode shapes of a rotor system with localized crack in several different position and depth, which will be treated as the input of the designed ANN model, can be obtained by repeating the above step. To insure the accuracy and quickness of the training process for the designed ANN model, a nonlinear model of a neuron is employed and a back-propagation learning algorism with Levenberg-Marquardt method is used.

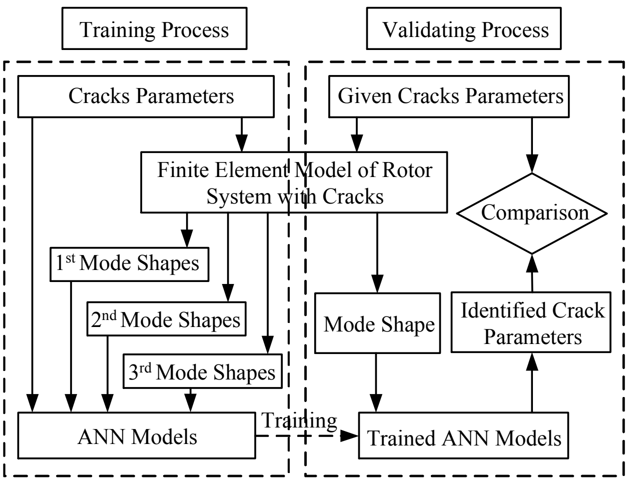

Fig. 1 Flow chart of identification scheme

Modes Calculation Based on FE Model of the Rotor System with Transverse Cracks

A type of rotating machinery classified to the category with high speed and light load can be considered as a jeffcott rotor, as shown in Fig. 2. It is assumed that the crack changes only the stiffness of the structure whereas the mass and damping coefficients remains unchanged. Cracks occurring in structures are responsible for local stiffness variations, which in consequence affect the mode shapes of the system. The FE model of rotor system with transverse cracks and a single centrally situated disc, and also the geometry of the cracked section of the shaft are shown in Fig. 3.

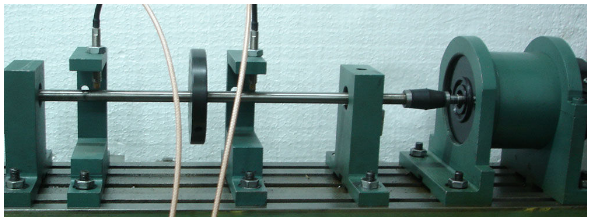

Fig. 2 A single-span-single-disc (jeffcott) rotor

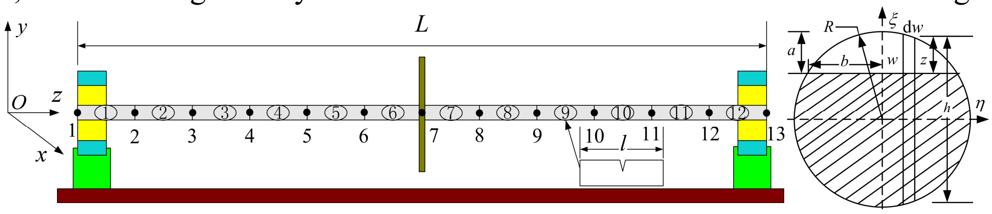

Fig. 3 The FE model of the rotor system and the geometry of the cracked section

Calculation of Total Stiffness Matrix of the Crack Element. According to the fracture mechanics and the energy principle of Paris, the additional strain energy due to a crack and calculation of caused cracks are given in the paper[5].

FE Modeling of the Rotor System. Assembling all the element mass, damping and stiffness matrices of the rotor system in stationary coordinate system, the equation of motion is

$$\boldsymbol{M}\ddot{z} + \boldsymbol{C}\dot{z} + \boldsymbol{K}z = \boldsymbol{F} \, . \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{K}$ and $\boldsymbol{F}$ are total mass, damping, stiffness and external exciting force matrices of rotor system respectively. z is the displacement of the element node.

Mode Shape of the Rotor System. For the rotor system considered in the paper, each beam element has two nodes and each node has two degrees of freedom representing transverse and deflecting displacements of the corresponding cross-section. Here, only the mode shape in the ξ-axis direction is discussed by assuming the rotor system is rigid supported at the bearing position.

The mode shape can be obtained by substituting $x_i = A^{(i)} \sin(\omega_i t + \varphi_i)$ into the homogeneous part of Eq.1 without considering the effect of the damping. Then, we get

$$(-\omega_i^2 \boldsymbol{M} + \boldsymbol{K}) A^{(i)} = 0 \, . \tag{2}$$

where ω_i and $A^{(i)}$ is the *i*-th nature frequency and eigenvector (mode shape).

The rotor system discussed in the present study, consisting of a 10 mm diameter shaft carrying a centrally situated steel disc with 50 mm diameter and 5 mm width, is divided into 12 elements as shown in Fig. 3. Using the method described before, the modes of different cases are calculated by introducing transverse cracks deliberately in the middle of certain element. For example, if two transverse case is taken into consideratrion, they may occured in element 2 and element 4 with diffferent depth. Given a specific crack with a depth ratio(a/R) 0.5 in element 2, the Fig. 4(a)~Fig. 4(c) are 1st mode shapes, 2nd mode shapes and 3rd mode shapes respectively with crack depth ratio in element 4 ranging from 0.01~1. The Fig. 4(d)~Fig.(f) shows the three mode shapes with a given crack depth ratio 0.5 in element 3 and the other crack depth ratio ranging from 0.01~1 in element 4.

For more multi-crack cases, the number of cracks may be 3 or more. In the paper, the case of 2 transverse cracks is mainly discussed.

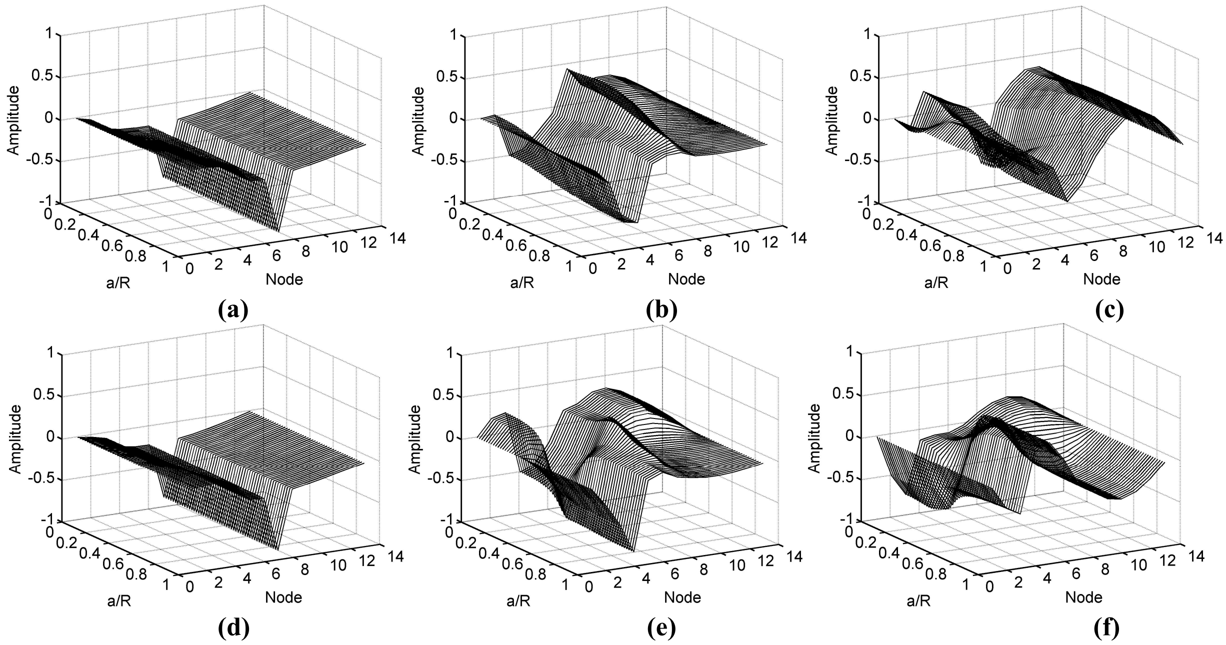

Fig. 4 The 1st, 2nd and 3rd modes of rotor system when two cracks occuring in different element

Artificial Neural Network Design

The architecture of a typical ANN model with back-propagation algorithm (BPA) is shown schematically in Fig. 4. In the paper, The Levenberg-Marquardt BPA and Nguyen-Widrow function are used in the ANN training and initialization of weights and biases for faster convergence and accuracy. The network architecture is built in terms of the numerals as N_I, N_{H1}, …, N_{Hn} and N_O, which denotes the number of neurons in the input layer, H_n^{th} hidden layer and output layer respectively. The input and target output for training are expressed respectively as $\boldsymbol{P}=[\boldsymbol{P}_1\ \boldsymbol{P}_2\ \ldots\ \boldsymbol{P}_n]$ and $\boldsymbol{T}=[\boldsymbol{T}_1\ \boldsymbol{T}_2\ \ldots\ \boldsymbol{T}_n]$, where $\boldsymbol{P}_i=[\boldsymbol{p}_1\ \boldsymbol{p}_2\ \ldots\ \boldsymbol{p}_m]_{13\times m}$ (i=1, 2, …, n), denotes the modes matrix corresponding to crack at a certain position with m kinds crack depth; $\boldsymbol{T}_i=[\boldsymbol{t}_1\ \boldsymbol{t}_2\ \ldots\ \boldsymbol{t}_m]_{12\times m}$ (i=1, 2, …, n), denotes the crack depth vectors corresponding with different position. That is to say, the target output vector is filled with values equal to 0 or a number between 0 and 1, and a value not equal to 0 is symbolic of the localization and depth of a crack. For example, the column vector $[0\quad 0.3\quad 0.5\quad \cdots\quad 0]^{T}_{12\times 1}$ indicates the presence of two cracks with depth ratio 0.3 and 0.5 occuring in the No.2 and No.3 element.

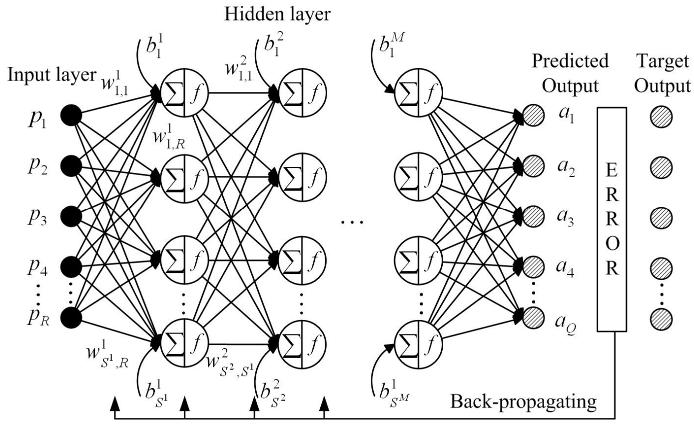

Fig. 5 The architecture of a BP ANN model

Training and Validation of the ANN

The training process can be started with the prepared training data and ANN model. To evaluate the effects of training data on the success of crack identification, different training scheme is designed. That is to say, with total 12 shaft elements, 2 cracks and 100 kinds of depth in each element corresponding to any type of 3 modes, the training data are arranged at intervals of 0, 1, 2, … and 14 respectively. Thus, 15 ANN models corresponding to each mode are trained. To compare the performances of the other trained ANN models, testing case excluded in the training data of different schemes are adopted as test cases, and the errors between predicted crack parameters (location and depth) and actual ones under different trained ANN models and test cases are illustrated in Fig.6, where the Fig. 6(a) and Fig. 6(d) show the performances of ANN models trained by 1st modes of the rotor system with two cracks of depth ratio 0.80 and 0.62 respectively. The Fig. 6(b)(e) and the Fig.6(c)(f) correspond to the performances with 2nd modes and 3rd modes respectively.

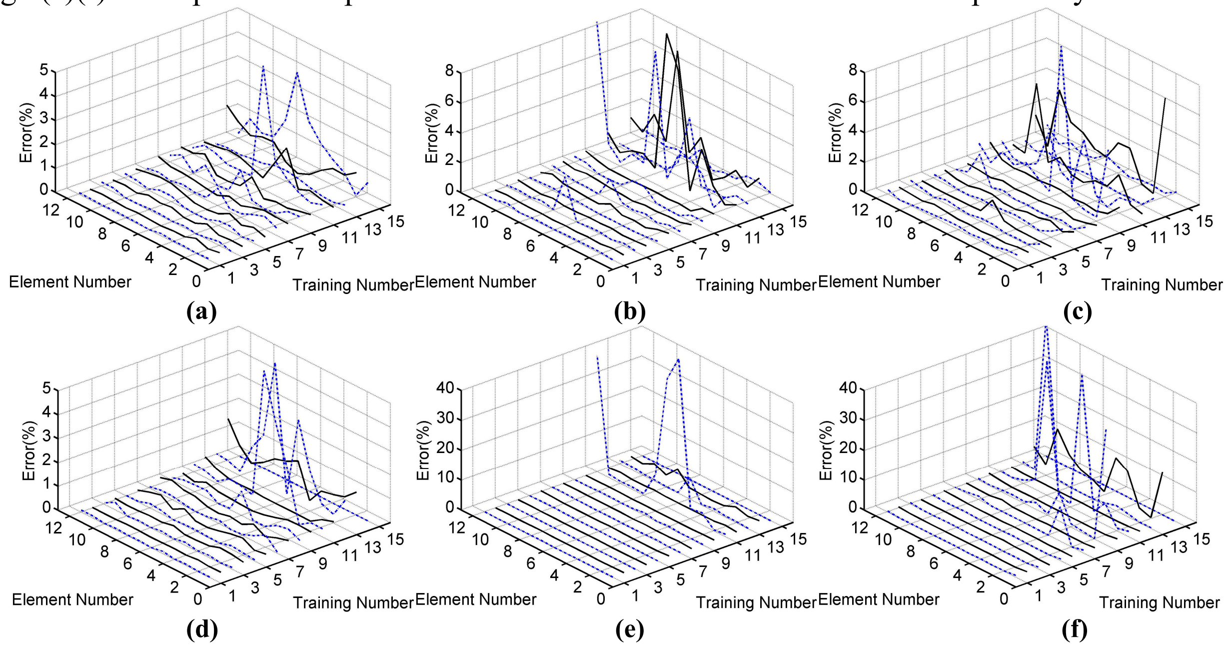

Fig. 6 Performances of different trained ANN models with two cracks case

It can be seen from Fig. 6 that the increase of the system modes order leads to performances of trained ANN models dropping down. Compare the performances of two cracks, it can be found that the shallower the crack, the bigger the errors. With the method and measured 1st mode shapes of cracked rotor system as shown in Fig. 2, the crack location and depth can be identified quantificationally to a good degree of accuracy with the trained ANN models.

Conclusion

By combining FE model of the rotor system and ANN models, non-destructively identification of multi-crack location and depth in rotating machinery is presented in the paper. With the ANN models trained by modes, especially the 1st modes of cracked rotor system, the given testing crack cases are identified to a good degree of accuracy. However, for a flock of calculation of ANN training, the computing time may be prolonged with the increase of the number cracks in the rotor system. So, the economical algorithm should be studied further.

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