Rotor Crack Fault Diagnosis based on Base and Multi-sensor Adaptive Weighted Information Fusion

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Abstract—**The faults of rotating machinery monitored by fixing the sensors on rotor directly brings some problems such as difficulty in fixing the sensors, poor universality and so on, while it brings some advantages such as rapidness, convenience and good universality and so on by fixing the sensors on the base. Since the base is far away from the fault source, the collected vibration signals are relatively weak. Multi-sensor information fusion method can describe the diagnostic object completely because it extends spatial and temporal limits, and obtains more information of the diagnostic object. A rotor crack fault diagnosis method based on base and multi-sensor adaptive weighted information fusion is proposed in this paper. The arrangement of the sensors on rotating machinery base was designed by taking advantage of the vibration transitivity of rotor-bearing-base and was verified by experiments. The adaptive weighted information fusion method is investigated, and the fault characteristic value is detected with multi-layer decomposition of wavelet analysis, and the fault of the cracked rotor is diagnosed effectively by combining with the Bode diagram in the process of speeding up. The research will provide a new method for the fault diagnosis of rotating machinery.**

Index Terms—**base, multi-sensor, adaptive weighted, information fusion, fault diagnosis**

I. Introduction

Large-scale rotating machineries such as steam turbo-generator, motor, fan, compressor and pump and so on are key production tools of modern enterprises in our country. With the development of science and technology, the higher and higher requirements to the performances of rotating machinery such as speed, capacity, efficiency and reliability and so on are proposed. When rotating machinery breaks down, it will not only affect the normal running of rotor system, but also lead to the serious accident such as shaft fracture in severe case, which causes the catastrophic damage to the whole rotating machinery system and enormous economic losses[1].

The current fault diagnosis method often takes the rotor as monitoring object directly. Sensors are installed usually on the bearing seat which is near to the rotor part, or fixed by special sensor support frames, which is very inconvenient in practical application and has the poor universality. Vibration signals are transferred to the base through the rotor and the supporting part during the rotor running, so the vibration signals of base also include the fault information. Taking the base as monitoring object to diagnose the fault of rotor has many advantages such as the convenience to fix sensors and good universality. However, current research in this area is rare because the base is far away from the fault source and the collected vibration signals are relatively weak. Multi-sensor information fusion method can describe the diagnostic object fully because it extends spatial and temporal limits, and obtains more information of the diagnostic object. A rotor crack fault diagnosis method based on base and multi-sensor adaptive weighted information fusion is proposed.

Oil-film sliding bearings are often used in the large-scale and high-speed rotor system frequently, and with the increase of rotational speed and motor power of rotating machinery, the influence between rotor system and base supporting becomes greater and greater. As to the rotor, sliding bearing and base, there are many differences in motion forms, materials and structures, and their motion forms are also very complex, so it is rare to build the whole finite element model[2-4]. The rotor-sliding bearing-base system model was built with ANSYS by considering the stiffness and damping coefficients of rotor and sliding bearings and the impacts of base synthetically, and the vibration characteristics of the base is investigated, and the sensor arrangement of the base is gained, and the arrangement is verified by experiments. The adaptive weighted information fusion method is investigated, the weighted values of all sensors on the base are calculated on the condition that the total mean-square error is minimums, and the fusion information is obtained according to the weighted values.

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The fault characteristic value is detected with multi-layer decomposition of wavelet analysis, and the fault of cracked rotor is diagnosed effectively by combining the Bode diagram in the process of speeding up.

II. Adaptive Weighted Algorithm

The basic idea of adaptive weighted algorithm is that, on the condition that the total mean-square error is minimums, the optimal weighted factors of various sensors which are sought by the adaptive way according to the measured value from the various sensors make the fused result optimal.

A multi-sensor information detection system is supposed, in which the detected object is tested with n sensors at the same time. The weighted fusion model is shown in figure. 1, x_1, ⋯, x_n are the test data from corresponding n sensors, p_1, ⋯, p_n are the weighted values of the corresponding test data, X is the fused result. The variances of the corresponding test data are assumed as σ_1^2, ⋯, σ_n^2, and all sensors are supposed to be independent, so the relationship of the fused result X between weighted value P_i can be expressed as formulas (1) and (2).

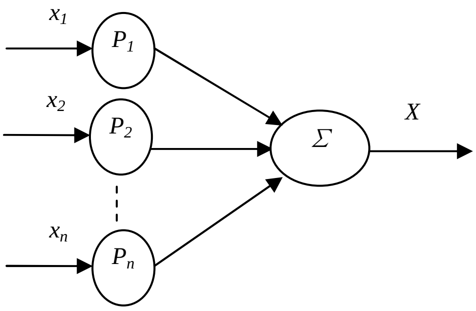


Fig.1 Weighted Fusion Model

$$X = \sum_{i=1}^{n} P_i x_i \tag{1}$$

$$\sum_{i=1}^{n} P_i = 1 \tag{2}$$

Because x_1, ⋯, x_n are independent, so the total mean-square error σ^2 can be expressed as formula (3).

$$\sigma^2 = \sum_{i=1}^{n} P_i^2 \sigma_i^2 \tag{3}$$

It is known from formula (3) that the total mean-square error σ^2 is the multiple quadratic functions of all weighted values, so the minimum must exist. The formula to calculate weighted value on the condition that the total mean-square error σ^2 is less on the basis of multivariate function for extreme value theory is as following equation.

$$P_i^{'} = 1/\sigma_i^2 \sum_{k=1}^{n} \frac{1}{\sigma_k^2} \quad (i=1, 2, \cdots, n) \tag{4}$$

So the procedure of adaptive weighted fusion is as follows. First, the variances of the corresponding test data σ_i^2 must be calculated. Second, the optimal weighted factor $P_i^{'}$ can be calculated according to formula (4). And then, the fused value X can be calculated according to formula (1).

III. System Modeling With ANSYS

Figure 2 is the real image of the rotor test bench. The solid model is built with PRO/E, and the finite element model is gained by importing the solid model into ANSYS and modified, as shown in figure 3. Two sliding bearings of the finite element model are simulated with two Matrix27 matrixes, one simulates stiffness matrix, the other simulates damping matrix. The dimension parameter values of all parts of rotor test bench are shown in table 1, and the material property parameter values of all parts of rotor test bench are shown in table 2.

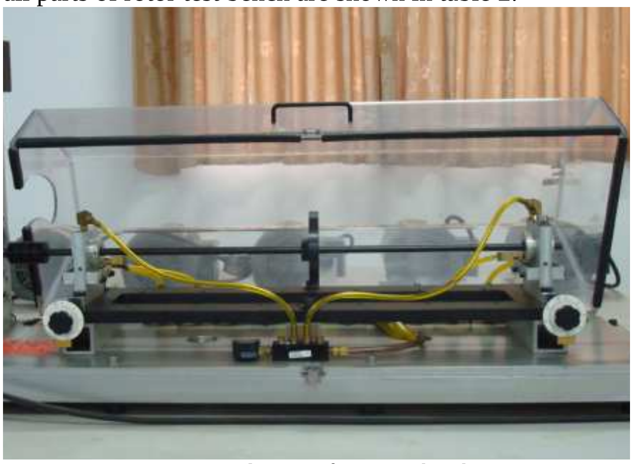


Fig. 2 Real image of rotor test bench

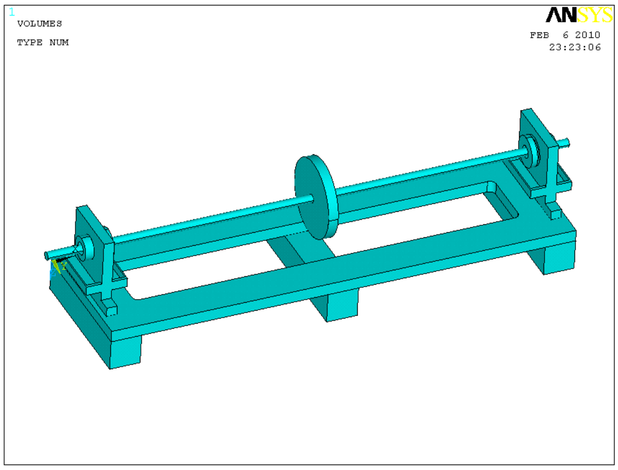


Fig. 3 Finite element model of rotor test bench

Table 1 Dimension parameter of rotor test bench

Name	Dimension (mm)	Name	Dimension (mm)	Name	Dimension (mm)
base /length	850	turntable /diameter	126	bearing seat /height	117
base /width	222	turntable /width	16	sliding bearing /inner diameter	13
rotor /length	850	bearing seat /length	146	sliding bearing /outer diameter	16
rotor /diameter	13	bearing seat /width	17	sliding bearing /width	9

Table 2 Material property parameter of the rotor test bench parts

Material Name	Density/kgm^{-3}	Elastic Modulus/MPa	Poisson Ratio	Parts name
aluminum alloy	2700	70000	0.35	base, bearing seat
copper	8200	130000	0.35	sliding bearing
steel	7800	210000	0.3	rotor, rotary table

Material parameter is given to each part of the rotor test bench model according to the table 2. The model is meshed by combining with sweep mesh method and local mesh method, and the mesh of the spindle and bearing block are refined. The meshed finite element model of rotor test bench is shown in figure 4.

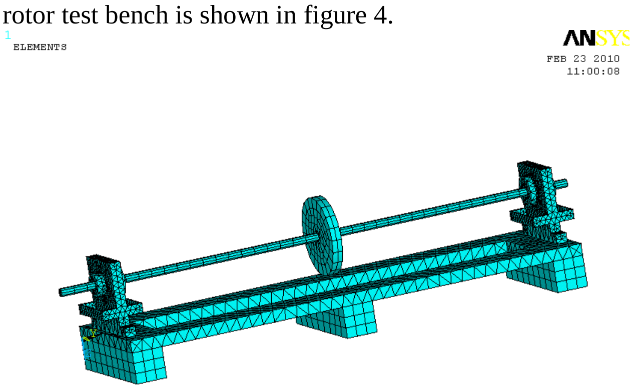


Fig. 4 Meshed finite element model of rotor test bench

IV. Vibration Characteristics Analysis Of Base Based On Transient Analysis

A *Loading and Solution*

According to the torque formula $T = 9550\,P/n$, in which, P is power, n is rotational speed, the motor power is 500 W, the rotational speed is 1800 r/min, so the torque T is $265.28\mathrm{N \cdot m}$. Based on the model of rotor test bench, the transient analysis is selected as analysis type in ANSYS solvers, and the Reduced method is chose to ascertain the transient responses which are changed with time and acted upon by the load, then the loading and solution are done. The torque-time cure of rotor test bench from starting to stable running is shown in figure 5.

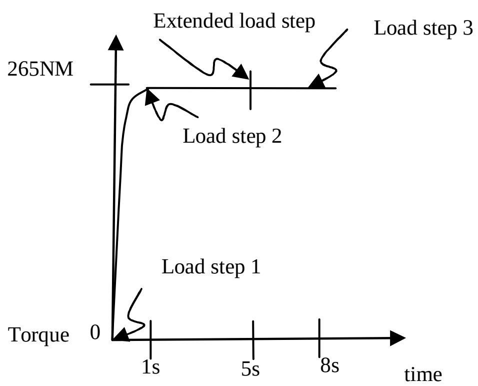
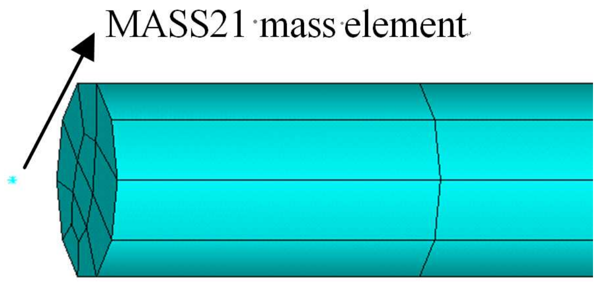
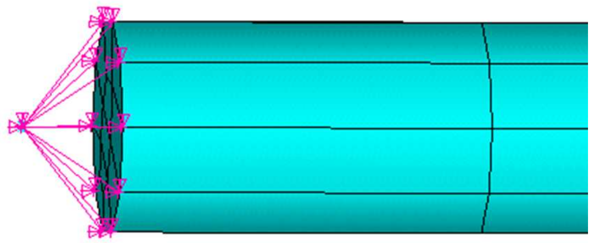


Fig. 5 Torque-time curve

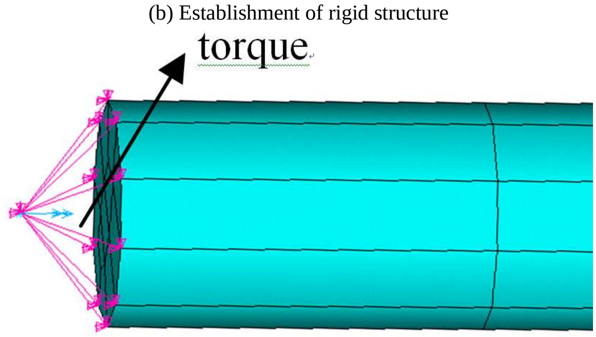
In the finite element analysis of mechanical structures, the torque loading can be converted into a pair of force loading which are same in size but opposite in direction. This method is visualized, but there are many limits in practical operations such as calculating the equivalent force on each node manually, heavy workload, and limit distribution of nodes and so on. From what has been discussed above, the torque loading is applied by means of Cerig. The main process is shown in figure 6. First of all, an independent node is generated at appropriate position on the center line of rotor, and the mass element is set as MASS21, as shown in figure 6 (a). Then a rigid structure between the node which sustains the real torque and the independent node is built by using Cerig command, as shown in figure 6 (b). Finally, the torque is applied on the MASS21 mass element directly, as shown in figure 6 (c).



(a) Generation of MASS21 mass element



(b) Establishment of rigid structure



(c) Application of torque

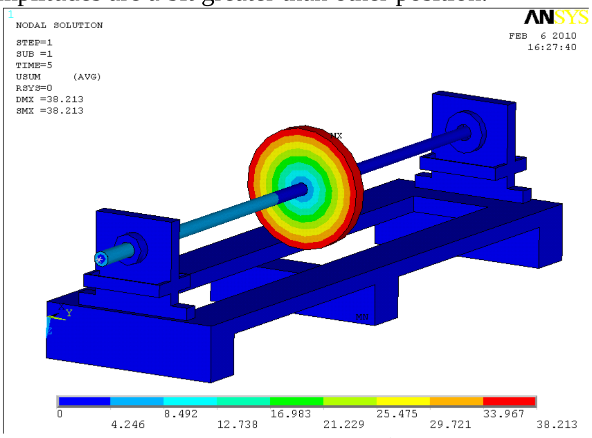
Fig. 6 Apply torque loading on rotor

B *Analysis Result*

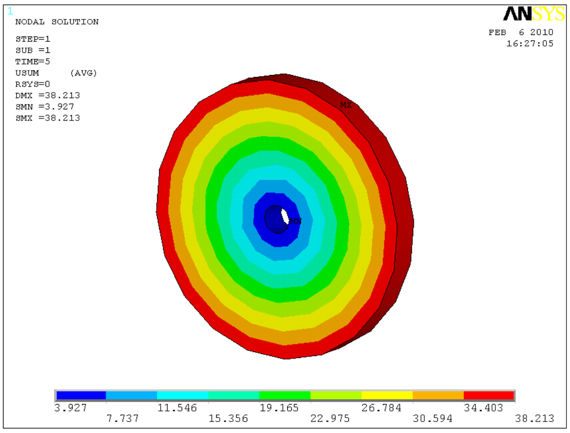
Through loading and solution, the values such as displacement of the corresponding node, stress-strain and so on can be exported with the postprocessor of ANSYS. The intensity of vibration signal is measured by the amplitude. Therefore, the displacements of the corresponding node are mainly analyzed in this chapter.

The equivalent displacement nephogram of the whole system is shown in figure 7. The equivalent displacement nephogram of the rotor test bench is shown in figure 7 (a), the equivalent displacement nephogram of the turnplate is shown in figure 7 (b), the equivalent displacement nephogram of the spindle is shown in figure 7 (c), the equivalent displacement nephogram of the shaft sleeve is shown in figure 7 (d), the equivalent displacement nephogram of the bearing block is shown in figure 7 (e), the equivalent displacement nephogram of the base is shown in figure 7 (f).

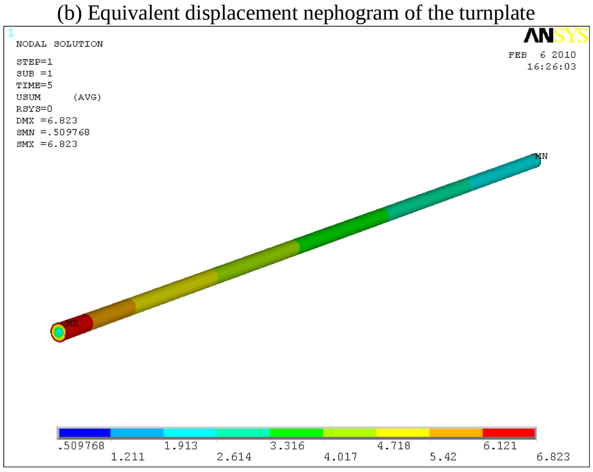
According to the results, it can be concluded that the maximum amplitude of vibration occurred at the turntable and the minimum at the base; the nearer to the shaft it is , the greater its amplitude is; some individual positions between base supports, as the special fields shown in figure 6, are ideal positions to install sensors, because they are located between the two constraints, and their amplitudes are a bit greater than other position.



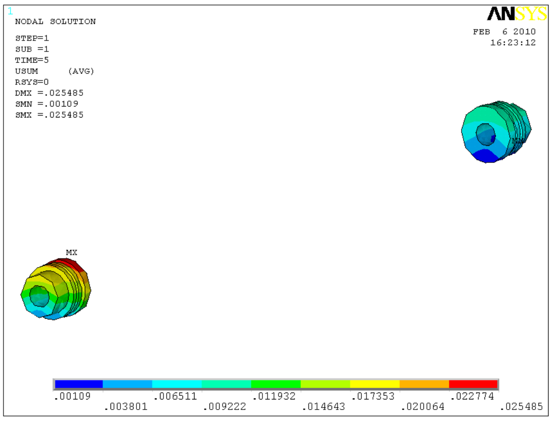
(a) Equivalent displacement nephogram of the rotor test bench



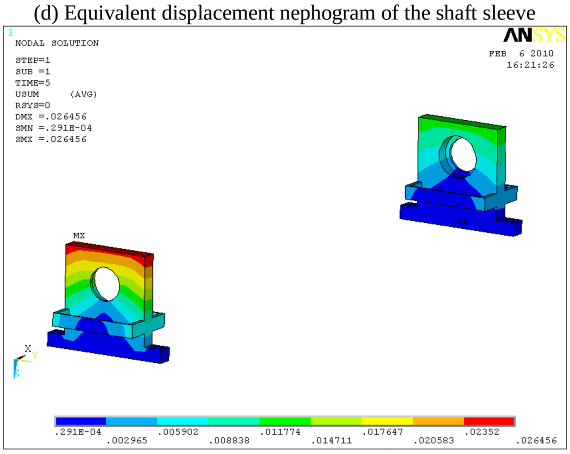
(b) Equivalent displacement nephogram of the turnplate



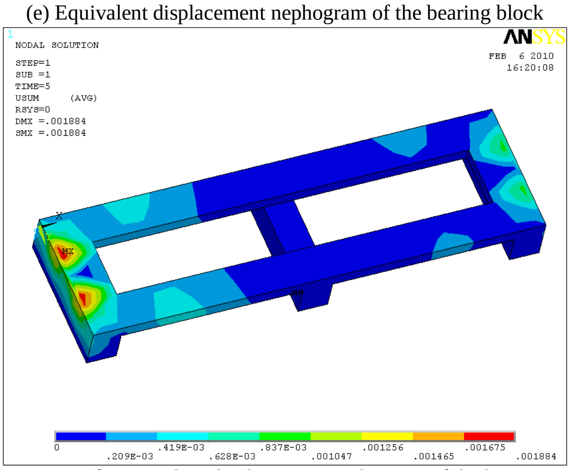
(c) Equivalent displacement nephogram of the spindle



(d) Equivalent displacement nephogram of the shaft sleeve



(e) Equivalent displacement nephogram of the bearing block



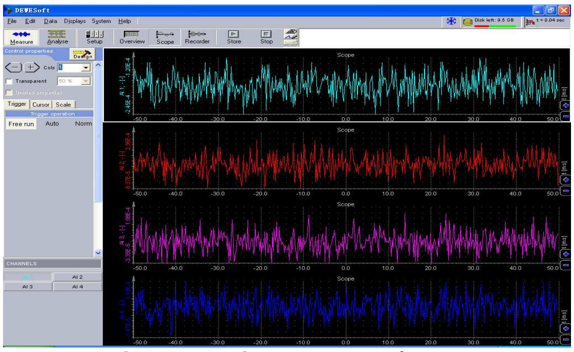
(f) Equivalent displacement nephogram of the base

Fig. 7 Equivalent displacement nephogram of the whole system

C *Experimental Verification*

The Dewetron data acquisition system is shown in figure 8, in which (a) is data acquisition card, (b) is data acquisition soft.

(a) Dewetron data acquisition card



(b) Dewetron data acquisition soft V6.2

Fig. 8 Dewetron data acquisition System

According to the base characteristic determined by ANSYS analysis, 6 sensors are arranged on the base, as shown in figure 9, whose serial number is from 1 to 6, a sensor is arranged on the bearing seat, whose serial number is 7.

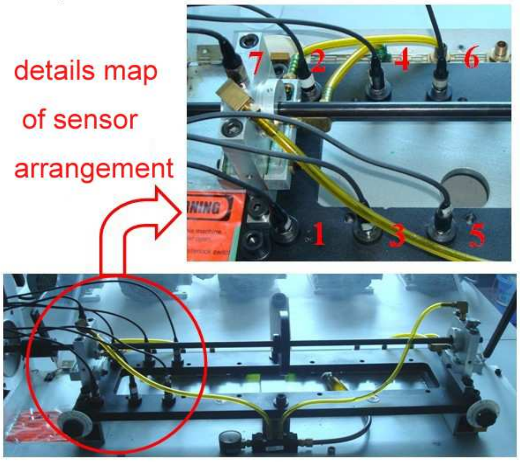


Fig 9. Sensor arrangement on the base

The correlation coefficient of the sensor signals is solved with correlation function method, as shown in formula (5). The correlation degree of two signals x and y is expressed by value of the ρ_{xy} , which value is between 0 and 1, the more similar waveform is, the closer to 1 the value is.

$$\rho_{xy}(\tau)=\frac{\int_{-\infty}^{\infty}x(t)y(t-\tau)dt}{\left[\int_{-\infty}^{\infty}x^2(t)dt\int_{-\infty}^{\infty}y^2(t)dt\right]^{1/2}} \tag{5}$$

The data of all sensors are sampled with Dewetron multi-channels' data sample system. Then the correlation coefficients of data between sensors 1-6 and sensor 7 are solved, and the results are shown in table 3.

Table 3 Correlation coefficients of sensors

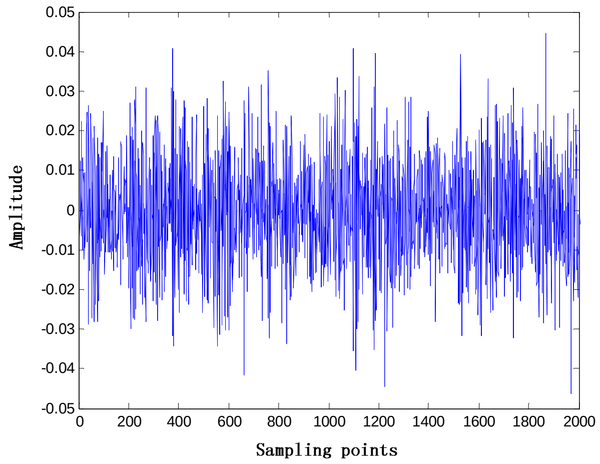
Sensor serial Number	Correlation Function Value
1	0.6301
2	0.6514
3	0.4701
4	0.4451
5	0.5672
6	0.6120

According to the results shown in table 3, the conclusion can be obtained that it is similar between the results of the experimental data analysis and the results of finite element analysis, the nearer with the bearing seat it is, the greater its correlation coefficient is, however, due to constraints of the bottom of the base, there is a little decline of the function value in the constraint place, which is consonant with the results of ANASYS finite element analysis. According to the values of the correlation coefficients of the sensors, the suitable places for sensor arrangement are 1, 2, 5 and 6.

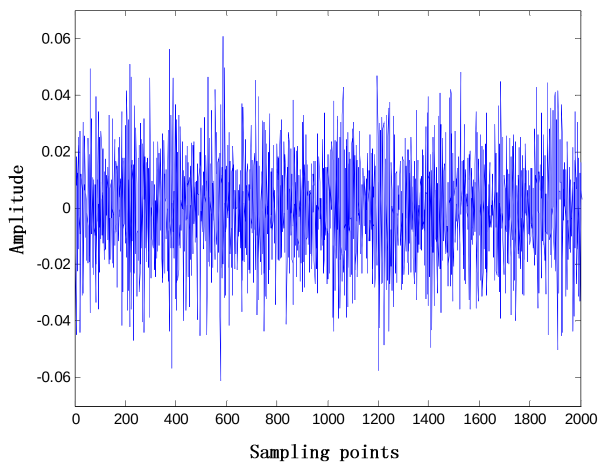
V. Multi-sensor Information Fusion Fault Diagnosis Based On Base

In order to research the effect of multi-sensor information fusion based on base combined with wavelet analysis in the fault diagnosis of rotor crack, the following experiments are done. Three rotor are prefabricated, the diameter of the rotor is 13mm and the length is 83mm, one rotor is uncracked, the other two are the rotors with various crack depth, and the crack incisions are reserved by wire-electrode cutting, then the cracks are made with fatigue test machine, the depth of the cracks are 3mm and 5mm respectively, the width of cracks are 0.11mm, the crack position locates in the central of rotor where is close to turntable, and a thin metals whose thickness is 0.10mm is embedded in crack to simulate the open or close of crack, and the thin metals is pasted with 502 glue to prevent it falling off in the experimental process. Through the theoretical analysis and experimental research, the critical speed of three rotors are 1640r/min, 1500r/min, 1380r/min respectively and the corresponding power frequencies are 23Hz, 25Hz, 27Hz respectively. The experiments are done on the rotor test bench which is made in Quest Spectra of American. The hardware of signal acquisition is 16 channel signal analyzer which is made in Dewetron Company of Austrian, and the software of signal acquisition is Dewesoft 6.2 which is mated with the analyzer. Sensors are the acceleration sensors which are mated with analyzer, the installation positions of the sensors are determined by the foregoing research on the arrangement of sensors on rotating machinery base, and the sampling frequency is 10000Hz.

The information fusion of the data of four sensors on the base is done with the adaptive weighted fusion algorithm, and the fusion signals are obtained. The time domain signal diagram (dimensionless) of the fusion signal of the cracked rotors which cracks are 3mm and 5mm respectively at the test speed of 1800r/min (rotor power frequency is 30Hz) is shown in figure 10, the figure 10 reveals that the time domain signal diagram contains a lot of noise signal, the valuable fault information cannot be obtained from the diagram. So the wavelet decomposition of the fusion signal must be done.



(a) 3mm crack depth



(b) 5mm crack depth

Fig. 10 Fusion signal time domain diagram

The 6 layer wavelet decomposition of both 3mm and 5mm crack depth fusion signals are done and the results are shown in figure 11 and figure 12 respectively. After decomposition each frequency band are d1 (2500-5000), d2 (1250-2500), d3 (625-1250), d4 (312.5-625), d5 (156.25-312.5), d6 (78.125-156.25), a6 (0-78.125) respectively. Since the fault frequency of the cracked rotor is high-frequency component such as 2 times frequency or 3 times frequency of the rotation frequency, so the d1, d2, d3, d4, d5 shown in figure 11 and figure 12 are the false high-frequency component and noise, while the signal characteristics of cracked rotor vibration can be reflected through the spectrum (0~156.25) of d6 and a6. The envelope spectrum analysis of the d6 and a6 are done and the spectrum characteristics of the requested spectrum can be gained and shown in figure 13. The figure 13 reveals the change of the spectrum diagram about cracked rotor on the initial stage (3mm) and later stage (5mm), along with the expanding and deepening of the crack, the components of fundamental frequency and times frequency increase steadily over the time.

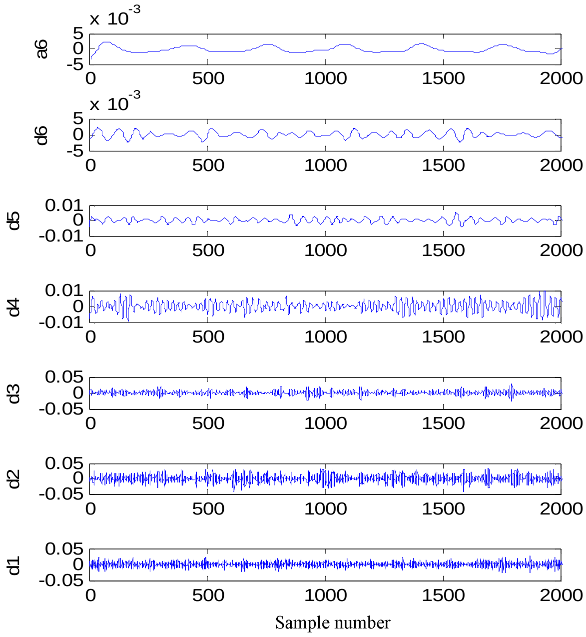


Fig. 11 Wavelet decomposition of 3mm crack depth fusion signal

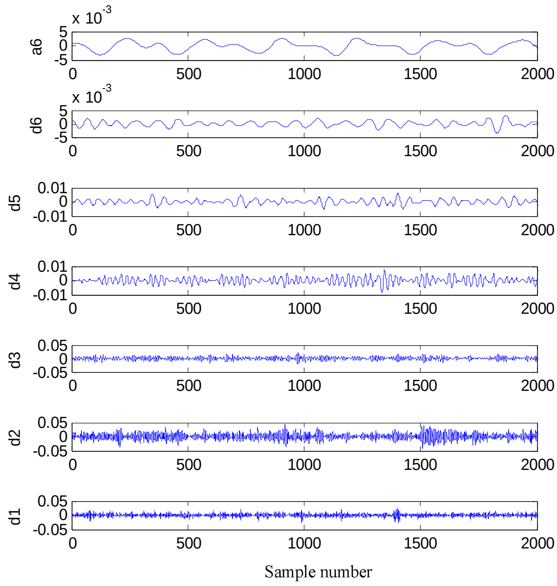
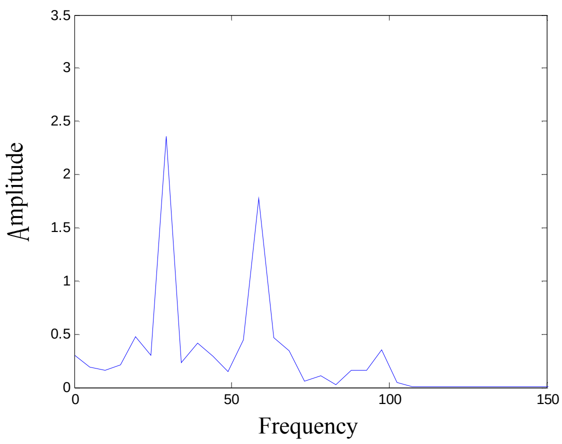
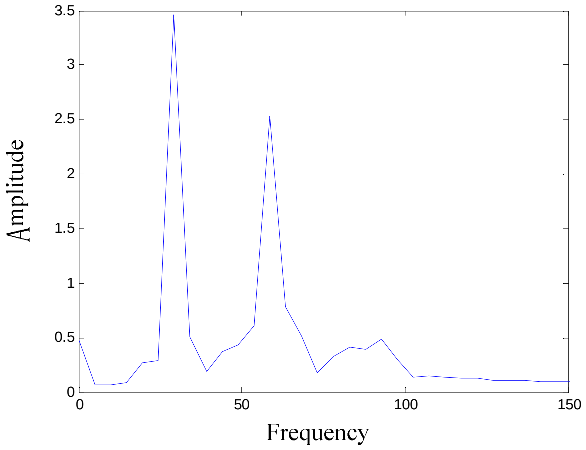


Fig. 12 Wavelet decomposition of 5mm crack depth fusion signal



(a) 3mm crack depth



(b) 5mm crack depth

Fig. 13 Spectrum comparison diagram of cracked rotor

Bode diagram (dimensionless) of the speed increase process of rotor which has 5mm crack is drawn, and the amplitude variation in the process is shown in figure 14. Figure 14 reveals that the amplitude of fusion signal changes obviously when the rotor speed is 1/2 times of first-order critical speed, which accords with characteristic that cracked rotor is very sensitive to the crack because of resonance and the amplitude of fusion signal will have a significant change. The conclusion that amplitude of fusion signal will have a significant change when the rotor speed is 1/2 times of first-order critical speed by the Bode diagram (dimensionless) of the speed increase process of rotor which has 3mm crack can also be obtained.

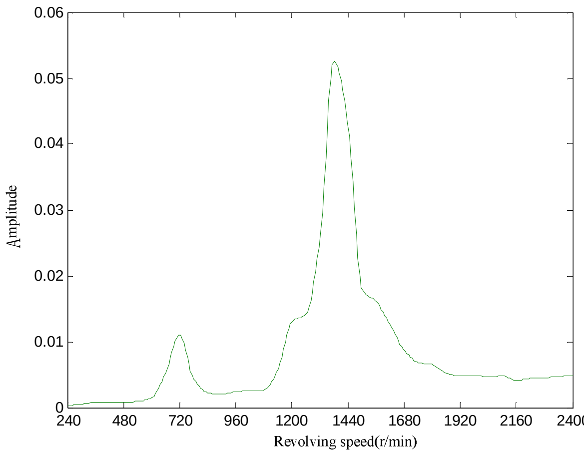


Fig. 14 Bode diagram of start process

Based on figure 13 and figure 14, it is proved that the fault of the cracked rotor is diagnosed effectively based on base and multi-sensor adaptive weighted information fusion and wavelet analysis.

VI. Conclusions

Taken rotor test bench as experimental platform, the finite element model of rotor-bearing-base system is built, the vibration characteristics of the base is gained with transient analysis of the model, and the relative factors which effect vibration characteristics of the base is investigated. The results of simulation are verified by experiments with correlation function method. The experimental results indicate that the sensor arrangement is valid. The adaptive weighted information fusion method is investigated, and the vibration signals from base are analyzed by the adaptive weighted fusion algorithm, and the fault characteristic value is detected with multi-layer decomposition of wavelet analysis, the fault diagnosis of cracked rotor with various crack depth is realized. The experiment results indicate that the proposed method can identify the crack fault of rotor effectively on the base of rotor test bench.

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