Research on Rotor Axis Orbit Measurement of High Speed Precision Spindle Under Unbalance Fault

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Abstract. Rotor axis orbit measurement can reflect a lot of running characteristics of the rotor, however, it’s hard to acquire the rotor axis orbit accurately for precision spindle, in particular the rotor of the high speed spindle is working under fault conditions. The most common fault of the high speed spindle is unbalance fault, which is must exist with the rotating machinery, also the unbalanced fault has a direct influence on the working precision of spindle. At the same time, the rotor axis orbit measurement result has often been influenced by the surface roundness error of the measurement object. In order to solve this problem, the error separation method is using for extracting the accurately rotor axis orbit, also the surface roundness error of the measurement object has been acquired. Compared with the rotor axis orbit measurement result under unbalance fault and balance state, though the measurement experiment, the rotor axis orbit measurement results are different and the surface roundness error separation results are almost the same. The experiment result prove that the unbalance fault could influence the result of the rotor axis orbit, but the surface roundness will not be influenced by the unbalance fault and it’s intrinsic attributes of the measurement object, in addition that the results verify the accuracy of the error separation algorithm.

Introduction

High speed manufacturing has become an important development direction in the field of manufacturing[1], because of the advantages such as high efficiency, low heat, good surface quality and so on. High speed precision spindle is the key part of high speed manufacturing, the performance of the high speed precision spindle determines the machining quality of the workpiece[2]. In order to realize the performance monitor and also acquire the fault characteristics of the high speed spindle, measurement has been used. There are many ways to get the information of the high speed precision spindle working condition, the scholars carried out a lot of studies on this by many technologies such as vibration acceleration testing technology, vibration velocity testing technology, vibration displacement testing technology and the acoustic emission testing technology[3,4]. But the technologies only have the unidirectional information of the spindle vibration, and it could not fully reflect the working condition of the spindle. In order to be able to fully acquire the information of the high speed precision spindle, more sensors have been used by different direction to obtain the effective information. The rotor axis orbit measurement technology could describe the performance of spindle by graph clearly, precisely and visually, because of using orthogonal vibration information, also be able to comprehensive reflect the moving condition of the high speed precision spindle rotor and then provide the important basis for spindle fault diagnosis[5]. However, it will be accompanied with the signal which constitute the rotor axis orbit by the surface roundness error, it will lead the rotor axis orbit result influence the judgement of spindle performance monitor condition, especially for the precision spindle[6]. It can be seen that the method of rotor axis orbit measurement is very important for the fault diagnosis result of spindle. The three point measurement method is a kind of error separation method, which could separate the measurement information into precisely rotor axis
orbit and surface roundness error of the measurement object. The accuracy of the separation results depend on the error separation algorithm. The verifying experiments will be taken by different working conditions of spindle in order to verify the accuracy of the error separation algorithm based on three point measurement method. The error separation method separate the surface roundness error from the rotor axis orbit measurement result, it will vastly reduce the influence of the surface roundness error to the result of spindle fault diagnosis. In addition the verifying experiments will show that the unbalance fault lead the rotor axis orbit to larger in graphic, thus it can be seen that the unbalance fault is the most important factor which cause the morphological change of rotor axis orbit measurement result after the surface roundness error separation.

**Rotor Axis Orbit Precision Measurement**

**Rotor Axis Orbit Measurement**

The rotor axis orbit is a kind of expression for the rotor axis position change in the radial direction and the result can be shown graphically, by using this measurement method it provides a way for spindle fault diagnosis visually. Usually two sensors have been set perpendicularly for rotor axis orbit measurement to acquire the radial direction vibration by horizontal and vertical direction, the basic rotor axis orbit measurement method can been shown graphically in Figure 1.

As it show in Figure 1 that the vibration signal acquired by the non-contact sensor not only contains the rotor vibration information, but also contains the surface roundness error of the measurement position, it can't satisfy the test requirements of the precision spindle. In order to reduce the influence by the surface roundness error to the rotor axis orbit measurement result, the standard bar and the standard ball is using as the measurement position by connect with the rotor. The API company and the LION company are all launched the products for rotor axis orbit measurement by using the standard ball. The product of LION company clearly demonstrates in Figure 2.

The measurement method of the product depicted in Figure 2 completely depend on the standard ball, the working spindle hold the cutter and cannot hold the standard ball at the same, so it could not be applied in the working spindle. Also the high speed precision spindle has high precision so that the vibration amplitude is nearly to the surface roundness error in the order of magnitude. So the surface roundness error separation method is desperately need for getting the accurately rotor axis orbit.

**Principle of Error Separation Method**

The purpose of error separation method is separating the surface roundness error from the rotor axis orbit measurement result. There are many common methods could realize the function, such as the reverse rotation method, isometric multistep rotation method and the three point measurement method[7], but the three point measurement method is more suitable for the working spindle in field
because of the characteristics as simple installation, convenient operation and high accuracy. The operating principle of three point measurement method is illustrated in Figure 3.

As an example, Figure 3 shows some details of the sensors acquire vibration signal process, the $R_i (i=1,2,3)$ is the distance of sensor to the desired rotor axis, the $r(\theta_n)$ is the surface roundness error, $e_x(\theta_n)$ and $e_y(\theta_n)$ is the actual position of the rotor axis. It can be express as the following relationship:

\[
\begin{align*}
S_1(\theta_n) &= R_i - r(\theta_n + \phi_1) - e_x(\theta_n) \cos \phi_1 - e_y(\theta_n) \sin \phi_1 \\
S_2(\theta_n) &= R_2 - r(\theta_n + \phi_2) - e_x(\theta_n) \cos \phi_2 - e_y(\theta_n) \sin \phi_2 \\
S_3(\theta_n) &= R_3 - r(\theta_n + \phi_3) - e_x(\theta_n) \cos \phi_3 - e_y(\theta_n) \sin \phi_3
\end{align*}
\] (1)

Because of the $R_i (i=1,2,3)$ is the fixed parameters, the surface roundness error $r(\theta_n)$ is the object variable, using constructor could elimination of the $e_x(\theta_n)$ and $e_y(\theta_n)$, so the constructor could be given by using equation(1):

\[
S(\theta_n) = a_1 r(\theta_n) + a_2 r(\theta_n + \phi_2) + a_3 r(\theta_n + \phi_3)
\] (2)

where the $a_1 = 1$, $a_2 = \sin(\phi_2)/\sin(\phi_3 - \phi_2)$ and $a_3 = \sin(\phi_3)/\sin(\phi_3 - \phi_2)$, it can be seen that the constructor only has the surface roundness error, the solution in frequency domain is given as the following equation:

\[
r(\theta_n) = \text{iffi}(S(\omega) / H(\omega))
\] (3)

where the $H(\omega) = a_1 e^{j\omega\phi_1} + a_2 e^{j\omega\phi_2} + a_3 e^{j\omega\phi_3}$ is the weight function, introducing equation(3) into equation(1), the position of the rotor axis could express as

\[
\begin{align*}
e_x(\theta_n) &= S_1(\theta_n) - r(\theta_n) \\
e_y(\theta_n) &= (S_2(\theta_n) - r(\theta_n + \phi_2) - e_x(\theta_n) \cos \phi_2) / \sin \phi_2
\end{align*}
\] (4)

Thus it can be seen that the three point measurement method is easy to implement, and the separation method has the precise mathematical model, in addition that it makes the method has high accuracy.

**Surface Roundness Error Separation**

In order to verify the separation effect of three point measurement method, the simulation roundness error signal and the rotor axis orbit signal is given as the equation:
\[
\begin{align*}
    r &= 10 + 0.1\sin(2\omega_0 t) + 0.2\cos(2\omega_0 t) - 0.6\cos(6\omega_0 t) + 0.3\sin(13\omega_0 t) + 0.7\cos(19\omega_0 t) \\
    e &= 1.3 + 0.5\cos(\omega_0 t + \pi/4) + 0.7\sin(2\omega_0 t + \pi/12)
\end{align*}
\] (5)

Though the equation (5), the roundness error signal is combined with many signals of different frequency, especially the high frequency signals are occupied the main position, and the high frequency signals lead the morphology of the roundness error to be more complex. Also as it can be seen that the rotor axis orbit signal contains rotational frequency signal and second harmonic generation signal.

By using the three point measurement method to separate the simulation signal, the separation results could be shown graphically in Figure 4.

![Figure 4. Separation results by using three point measurement method.](image)

Though the separation results from Figure 4, the separation roundness error is very nearly to the simulation roundness error, thus it shows the separation method has high accuracy, so the rotor axis orbit by separation is close to the simulation data and the morphology of the rotor axis orbit is completely conforms to the characteristic of simulation signal.

**Verifying Experiment under Unbalance Fault**

The three point measurement method is able to realize accurate rotor axis orbit acquisition, fault diagnosis result will be more accurate by using this method for the high speed precision spindle. The unbalance fault influence the morphology of rotor axis orbit, however, the influence will often be submerged in the roundness error and the noise and it’s hard to get the accurate rotor axis orbit. Using three point measurement method to separate the roundness error for the high speed precision spindle under the unbalance fault, and the accurate rotor axis orbit will be acquired, in order to realize it the verifying experiment is taken, the verifying experiment field is shown in Figure 5.

![Figure 5. Verifying experiment field.](image)

The high speed precision spindle is chosen as experiment object, the highest speed of spindle could reach 35000r/min, on the front end of the spindle there is an additional weight disk for change the balance condition. The signal acquisition system is composed with the sensors, power supply,
data acquisition card as well as the computer with the acquisition software. The product of micro-epsilon measurement company as eddyNCDT3010-U05 non-contact displacement sensors is using for get the vibration signal, and the USB4432 data acquisition card from NI company is using for data acquisition.

Though the experiment field that the measurement signal could be obtained as 20 kHz sample frequency by using the signal acquisition card and the spindle is working under 12000r/min. Using three point measurement method to acquire the measurement signal, then the accurate rotor axis orbit has been left by separating the roundness error, the result is illustrated in Figure 6.

Figure 6 clearly demonstrates that the roundness error is nearly the same, and the morphology of rotor axis orbit has been changed under the unbalance fault, also it has the bigger vibration amplitude under the unbalance fault.

**Summary**

Rotor axis orbit measurement is the most effective way to the performance monitor and also acquire the fault characteristics for the high speed precision spindle, but the common rotor axis orbit measurement product cannot satisfy the demand of the high accuracy measurement. In this paper, the conclusion has been got as

1. The three point measurement method could separate the surface roundness error from the rotor axis orbit measurement result, with the characteristics as simple installation, convenient operation and high accuracy, using the method high accuracy will be acquired and it provide necessary information to do fault diagnosis for the high speed precision spindle.

2. The roundness error is the inherent property of the measurement point on the rotor, it will not be influenced by the working condition, even the spindle is working under the fault condition, and the unbalance fault is able to influence the morphology of rotor axis orbit.

The method in this paper is easy to implement, and has the precise mathematical model, in addition that it makes the method has high accuracy. It must has wider prospect of application.

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**References**


