FIELD BALANCING TECHNIQUE OF A CENTRIFUGE FOR COMBINED ENVIRONMENTAL TEST

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Field balancing technique of a disc centrifuge for combined environmental test is presented. Considering the influence of machining error of the rotor, a novel method of signal acquisition is put forward to detect the machining error and pick up the real unbalanced vibration signal. The correlation filtering method is adopted to obtain the amplitude and the initial phase of vibration signal simultaneously. The mass-radius product and the phase of the original unbalance are identified by the influence coefficients method. Experimental results show that the proposed field balancing technique reduces the amplitude of the vibration from 29.7μm to 2.1μm.

Keywords: field balancing, centrifuge, combined environmental test, correlation filtering, influence coefficients method.

1. Introduction

In the aerospace industry, the reliability of aerospace components is paid more and more attention. It has been evaluated that environmental factors are mainly responsible for the failure or damage of spacecrafts. Therefore, sufficient combined environmental tests which can simulate the environment in real application are demanded on the ground before launching [1, 2]. Centrifuges are always employed to simulate the linear acceleration and play the main part of combined environmental testing devices [3, 4]. Dynamic balancing is a key technique for centrifuges. Due to the large dimension of a centrifuge and a large amount of equipments installed on it, it is impossible to balance the centrifuge on

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a balancing machine except field balancing. However, there are no reports of field balancing for this type of centrifuges.

Non-contact measurement of the vibration through displacement sensors has been developed in many studies [5-8], but the influence of machining error of the rotor was not considered. X.G. Shang and F. Zhang evaluated the relationship between the machining error of the rotor and the harmonic component of the vibration signal with FFT [9]. However, the detailed machining error was not got. Considering the machining error of the rotor, Y.F. Yang and X. Huo studied the balancing method of a disc centrifuge, in which the unbalance was worked out by testing the tilt angle of the shaft [10]. The disadvantage is that two displacement sensors are needed and the mounting positions of the sensors must be very precise.

Generally, the amplitude and the initial phase of the vibration signal are obtained separately. The vibration signals are sampled by vibration sensors, while the reference phase is provided by a phase reference sensor. The initial phase of vibration is obtained by comparing the vibration signal with the reference signal in the time domain [11, 12]. If the FFT is applied, the amplitude and the initial phase can be obtained simultaneously [13]. However, as the sampled signal is always contaminated, the signal processing is highly required.

In this study, a low cost displacement sensor fixed on the ground is installed beside the rotor of the centrifuge to measure the vibration of the centrifuge. Considering the influence of machining error of the rotor, a novel method of signal acquisition is put forward to detect the machining error and pick up the real unbalanced vibration signal. Moreover, the amplitude and the initial phase of the vibration signal are worked out simultaneously by the correlation filtering method, which is not sensitive to the white noise. The mass-radius product and the phase of the original unbalance are identified by the influence coefficients method. Finally, the centrifuge is balanced by installing a mass which forms the same mass-radius product at the opposite phase of the original unbalance.

2. Acquisition of the unbalanced vibration signal

2.1 Structure of the signal acquisition system

The structure of the signal acquisition system is shown in Fig. 1. Due to the special structure of the centrifuge, it is not convenient to install accelerometers near its bearing. Instead, an eddy current sensor fixed on the ground is installed beside the rotor to measure the displacement variation of the gap between the rotor and the sensor, which represents the radial vibration of the centrifuge. As the diameter of the rotor reaches about 1.6 m, the roundness of the rotor is considerable due to its large diameter, which will affect the measured displacement of the vibration when rotating. In other words, the machining error of the rotor cannot be ignored and must be eliminated after vibration signals are sampled.

As shown in Fig. 1, the output of the sensor is input to the data acquisition card, which communicates with PC through USB bus. A magnet on the rotor is applied as the phase reference of the vibration. A Hall switch fixed on the ground will output a pulse once in each revolution of the rotor when it meets the magnet. The pulse signal of the Hall switch is employed as the start signals for the data acquisition card. The rotating speed of the rotor is measured by counting the pluses of a photoelectric encoder mounted on the shaft, which is connected to the rotor by gear transmission. As we know, the photoelectric encoder provides a pulse at each gear tooth passage, disregarding its angular speed. Therefore, by employing the pulse sequence of the photoelectric encoder as the triggering signal of the data acquisition card, the displacement sequence of the vibration is sampled at fixed positions in each revolution of the rotor, regardless of the change of the rotating speed.

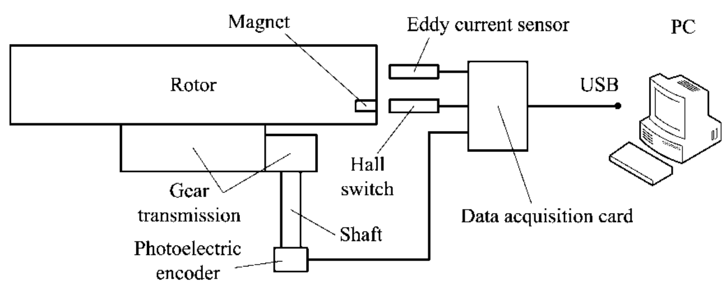

Fig. 1. Structure of the signal acquisition system

The process of the data acquisition is shown in Fig. 2. After receiving the start signal from the Hall switch, the data acquisition card is ready for sampling. Then, the card samples once when the photoelectric encoder outputs an impulse signal. The card transmits the sampled data to the PC until N_S points are sampled. N_S is carefully chosen to ensure integral period sampling when the rotor has just rotated N_T rounds. At this point, one sampling process is completed.

2.2 Detection of the unbalanced signal

The machining error is obtained as follows: the rotor is manually pushed to rotate N_T rounds at a very low speed which ensures the vibration amplitude caused by unbalance is almost 0, and then the machining error sequence $e(n)\,(n = 1, 2, ..., N_S)$ is obtained by the data acquisition system.

The vibration sequence $z(n)\,(n = 1, 2, ..., N_S)$ is sampled when the rotor rotates N_T rounds at a higher speed. Notice that the sampling points are the same as the sampling points at low speed stated above because the start signal and the triggering signal is not changed. In this case, the real vibration signal $x(n)$ caused by the unbalance is obtained by subtracting the machining error $e(n)$ from the vibration curve $z(n)$, that is

$$x(n) = z(n) - e(n). \tag{1}$$

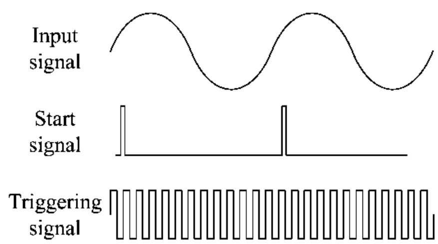

Fig. 2. Process of the data acquisition

3. Principle of balancing

3.1 Calculation of the amplitude and phase of the vibration signal

According to the correlation filtering method, the vibration signal can be assumed as [14]

$$x(n) = A_0 + A_1 \sin\left(\frac{2\pi}{N_S/N_T} n + \varphi_1\right) + \sum_{i=2}^{\infty} A_i \sin\left(\frac{2\pi \cdot i}{N_S/N_T} n + \varphi_i\right) + B(n), \tag{2}$$

where $x(n)$ is the sampled signal, A_0 is the DC component, $A_1 \sin\left(\frac{2\pi}{N_S/N_T} n + \phi_1\right)$ is the vibration signal at the fundamental frequency, $A_i \sin\left(\frac{2\pi \cdot i}{N_S/N_T} n + \phi_i\right)$ is the vibration signal at the ith harmonic frequency, $B(n)$ is the noise, N_T is the number of signal periods, and N_S is the total sampling points.

Let $x_1(n) = \cos\left(\frac{2\pi}{N_S/N_T} n\right)$, $x_2(n) = \sin\left(\frac{2\pi}{N_S/N_T} n\right)$ where $n = 1, 2, ..., N_S$, and assume that

$$\begin{cases} Y_1 = \sum_{n=1}^{N_S} x(n)\cdot x_1(n), \\ Y_2 = \sum_{n=1}^{N_S} x(n)\cdot x_2(n). \end{cases} \tag{3}$$

Due to the integral period sampling, the following equations hold

$$\begin{cases} \sum_{n=1}^{N_S} A_0 \cos\left(\frac{2\pi}{N_S/N_T} n\right) = 0, \\ \sum_{n=1}^{N_S} A_1 \sin\left(\frac{2\pi}{N_S/N_T} n + \varphi_1\right)\cos\left(\frac{2\pi}{N_S/N_T} n\right) = \frac{1}{2} N_S A_1 \sin\varphi_1, \\ \sum_{n=1}^{N_S} \sin\left(\frac{2\pi\cdot i}{N_S/N_T} n + \varphi_i\right)\cos\left(\frac{2\pi}{N_S/N_T} n\right) = 0. \end{cases} \tag{4}$$

And if the number of sampling periods is large enough, then

$$\sum_{n=1}^{N_S} B(n)\cdot\cos\left(\frac{2\pi n}{N_S/N_T}\right) = 0. \tag{5}$$

Therefore,

$$Y_1 = \frac{1}{2} N_S A_1 \sin\varphi_1. \tag{6}$$

Similarly, it can be got that

$$Y_2 = \frac{1}{2} N_S A_1 \cos\varphi_1. \tag{7}$$

Therefore, the amplitude of the vibration signal is obtained by

$$A_1 = \sqrt{\left(2Y_1/N_S\right)^2 + \left(2Y_2/N_S\right)^2}, \tag{8}$$

and the initial phase of the vibration signal is obtained by

$$\varphi_1 = \begin{cases} \arctan\left(\frac{Y_1}{Y_2}\right), & Y_1 > 0, Y_2 > 0 \text{ or } Y_1 < 0, Y_2 > 0 \\ \arctan\left(\frac{Y_1}{Y_2}\right) + \pi. & Y_1 > 0, Y_2 < 0 \text{ or } Y_1 < 0, Y_2 < 0 \end{cases} \tag{9}$$

3.2 Elimination of the original unbalance

Suppose that the rotor of the centrifuge is rigid, the mass-radius product and the phase of the original unbalance can be worked out by the influence coefficients method [15]. Driving the rotor to rotate at its maximum speed, the amplitude A_1 and the initial phase φ_1 of the original vibration signal are obtained through the above method, which is in the complex form of $A_1 e^{j\varphi_1}$. Next, a trial mass m_1 is installed at phase β and radius r_1 on the rotor and the rotor is driven to rotate at the same speed again. After the trial mass is installed, the vibration signal is obtained as $A_2 e^{j\varphi_2}$. According to the principle of the influence coefficients method, the original unbalance of the rotor is

$$\boldsymbol{U} = \frac{A_1 e^{j\varphi_1}}{A_2 e^{j\varphi_2} - A_1 e^{j\varphi_1}} \cdot m_1 r_1 e^{j\beta}. \tag{10}$$

According to the modulus $|\boldsymbol{U}|$ and argument $\angle \boldsymbol{U}$ of the complex $\boldsymbol{U}$, the centrifuge can be balanced by installing a mass which forms a mass-radius product of $|\boldsymbol{U}|$ at the phase of $\angle \boldsymbol{U} + 180^\circ$.

4. Experimental results

The prototype of the centrifuge for combined environmental test is shown in Fig. 3. As the gear ratio of the centrifuge is 141/29, 29 rounds of the centrifuge are set as one sampling process to ensure accurate integral period sampling, namely $N_T = 29$ is set. In order to reduce the acquisition error, the data used in the calculation is the average value of ten sampling processes.

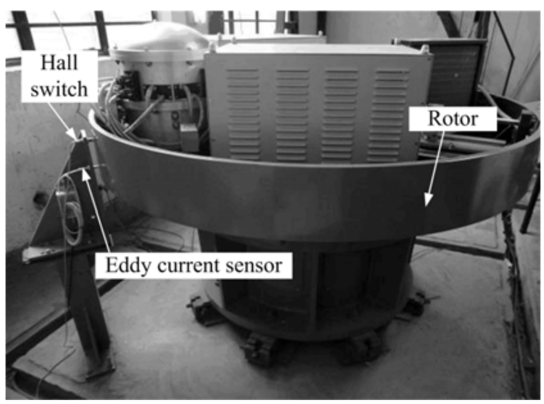

Fig. 3. Prototype of the centrifuge

First of all, the machining error curve is detected and drawn in Fig. 4. Then the vibration caused by the original unbalance is measured and shown as the gray solid line in Fig. 5 with the machining error eliminated, where the centrifuge is at its maximum speed (130 r/min). The sine curve of the vibration is shown as the black dotted line in Fig. 5, which is drawn according to the amplitude and the initial phase obtained by the correlation filtering method. From Fig. 4 and Fig. 5, it could be found that the machining error of the rotor is about 60μm peak to peak, as well as the vibration signal of the original unbalance. Therefore, the machining error cannot be ignored and must be eliminated.

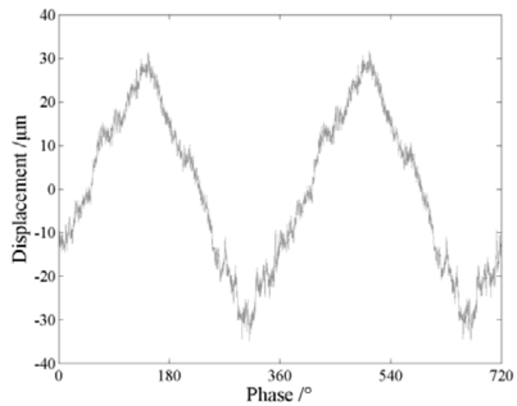

Fig. 4. Curve of the machining error

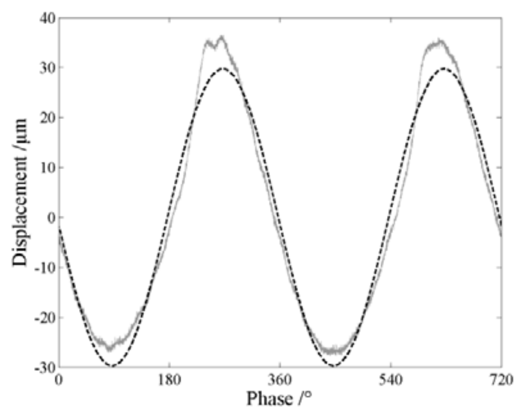

Fig. 5. Vibration caused by the original unbalance

A trial mass of 14 kg is installed on the rotor at the phase of 150° and radius of 0.715 m. The vibration with the trial mass installed is drawn as the gray solid line in Fig. 6 with the machining error eliminated, where the centrifuge is at its maximum speed (130 r/min). The sine curve of the vibration is shown as the black dotted line in Fig. 6, which is drawn according to the amplitude and the initial phase obtained by the correlation filtering method.

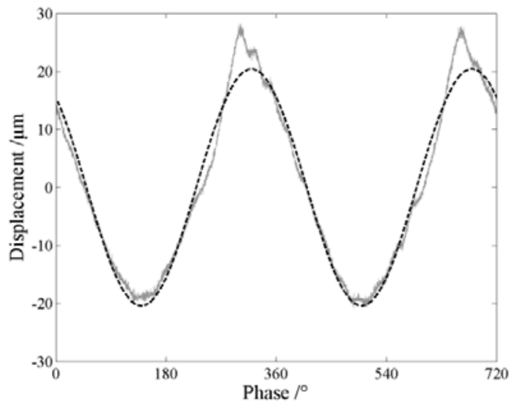

Fig. 6. Unbalanced vibration after trial mass installed

According to the amplitudes and the initial phases of the original unbalanced vibration and the unbalanced vibration after the trial mass is installed, the mass-radius product and the phase of the original unbalance can be worked out by the influence coefficients method. The calculation result shows that a mass of 17.5 kg should be installed at the phase of 108.5° and the radius of 0.715 m to balance the centrifuge.

The vibration after the centrifuge is balanced is drawn as the gray solid line in Fig. 7 with the machining error eliminated, where the centrifuge is at its maximum speed (130 r/min). The sine curve of the vibration is shown as the black dotted line in Fig. 7, which is drawn according to the amplitude and the initial phase obtained by the correlation filtering method.

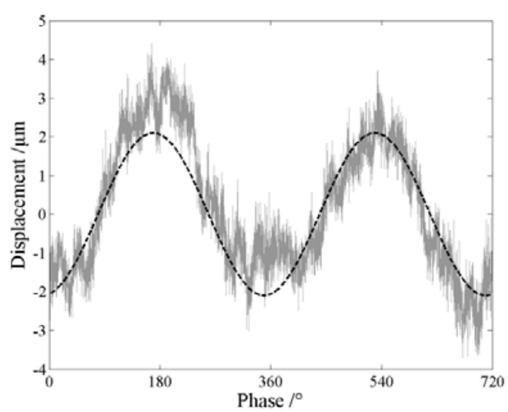

Fig. 7. Balanced vibration

As shown in Fig. 5-7, the sine curve of the vibration, which is drawn according to the amplitude and the initial phase obtained by the correlation filtering method, almost coincides with the curve of the sampled vibration. This indicates that the correlation filtering method can be applied to extract the amplitude and the initial phase of the contaminated vibration signal.

The experimental results are listed in Table. 1. Using the field balancing technique proposed in this paper, the amplitude of the vibration is reduced from 29.7μm to 2.1μm. This proves that the influence coefficients method can be applied to reduce the radial vibration of the centrifuge.

Table 1

Experimental results

States	Amplitude (μm)
Original vibration	29.7
Vibration after trial mass installed	20.4
Balanced vibration	2.1

5. Conclusions

A novel field balancing technique is proposed to balance a disc centrifuge with large diameter, which cannot be balanced on the balancing machines. As it is not convenient to install accelerometers near its bearing, a displacement sensor fixed on the ground is installed beside the rotor to measure the radial vibration of the rotor. Considering the influence of machining error of the rotor, a novel method of signal acquisition is put forward to detect the machining error and obtain the real vibration signal. A magnet and a Hall switch are installed to provide the phase reference of the vibration and the start signal of the data acquisition card. The pulse sequence of the photoelectric encoder is employed as the triggering signal of the data acquisition card, which ensures that the sampling positions are fixed within each sampling period, regardless of the change of the rotating speed. As a result, the machining error is detected and eliminated by subtracting it from the sampled vibration. The experimental results show that the amplitude and the initial phase of the contaminated vibration signal could be worked out by the correlation filtering method, and the centrifuge could be balanced well by the influence coefficients method. The proposed field balancing technique could be popularized in balancing centrifuges for combined environmental test or other applications.

Acknowledgments

This research is sponsored by the Science Fund for Creative Research Groups of National Natural Science Foundation of China (Grant No. 51221004), the Zhejiang Provincial Science Fund for Distinguished Young Scholars in China (Grant No. LR12E05001), the Key Science and Technology Innovation Team Program of Zhejiang Province in China (Grant No. 2009R50008), the National High-Tech Research and Development Program of China (Grant No. 2007AA04Z440), the National Natural Science Foundation of China (Grant No. 51375443) and the Zhejiang Provincial Natural Science Foundation of China (Grant No. LQ12E05011).

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