Study on online active balancing system of rotating machinery and target control method

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Abstract: - In order to reduce the unbalance vibration of the rotating machinery automatically during the work process, a new type of liquid-transfer active balancing system was proposed. In the system, a balancing disc divided into four liquid storage chambers was mounted on the rotor. When the unbalance response of the rotating machinery was higher than the limiting value, compressed air was injected to the target chambers and drove the balancing liquid to transfer between opposite chambers. Through the liquid redistribution in the balancing disc, a correction mass was generated to compensate the initial unbalance. The balancing device could be mounted both in the middle of rotor and at two ends. A target control method utilizing influence coefficients was also proposed to determine the balancing target and calculate the time of gas injection. Different control paths would generate different balancing effects, so simulations on several control paths were done to find the optimal solution. In addition, two experimental devices were constructed and active balancing experiments were carried out to verify the feasibility and availability of the balancing system.

Key-Words: - Rotating machinery; Unbalance vibration; Active balancing; Liquid transfer; Compressed air; Target control

1 Introduction

Mass imbalance of rotor is one of the common faults for the rotating machinery. In the machining process, machine tools need to be changed frequently. Even though the tools are pre-balanced before installation, small misalignment in the installation and uneven wear in the working process will also destroy the initial balance and then affect the precision of work pieces. In the industrial production, rotating machines such as turbo-machine are the core equipments for the production chain. Once the unbalance response is higher than the limiting value, operations people must stop the machines and do off-line balancing, such as the dynamic balancing for rotor on dynamic balancer and field balancing for the whole machine balancing. If there is no backup machine, the production is interrupted, which causes a great amount of economic losses. The demand of engineering makes people to research the on-line automatic balancing technology which is done automatically to reduce the unbalance vibration of rotor with the rotating machine running. On-line automatic balancing is helpful to improve operation efficiency and accuracy, reduce the downtime due to unbalance fault, and ensure the long-term running of machines.

On-line automatic balancing can be divided into two categories: passive balancing and active balancing. The working principle of passive balancing originates from the self-alignment phenomenon when the rotation speed of the system exceeds its critical speed. Therefore, passive balancing only applies to the flexible rotor. Due to the different balancing medium, passive balancing can be grouped into several types, such as ball balancing [1], hydraulic balancing [2], pendulum balancing [3]. Active balancing can be further divided into two categories: magnetic force balancing and mass redistribution balancing. The magnetic force balancing system such as electromagnetic bearings directly applies rotating electromagnetic force to compensate rotor imbalance [4, 5]. For the mass redistribution balancing, a balancing actuator corotating with the rotor is used to reduce unbalance response [6-9]. Through the mass redistribution of the balancing actuator, a correction mass is generated to compensate the initial unbalance.

Liquid active balancing, which has a balancing disc to store balancing liquid, is one type of mass redistribution balancing. The balancing disc is evenly divided into three or more annular chambers. The liquid redistribution of balancing disc is used to produce the correction mass online. Dieter et al. presented a liquid injection balancer for the first time in 1976 [10]. It had a simple construction, was easy to manufacture and didn't have movable assembly in rotating part, which made it the perfect solution for high speed application. However, such a balancer also had several disadvantages: (1) the liquid injection subordinate system was complex and expensive, (2) the balancing capacity decreased with increasing balancing number, (3) the balanced state could not be maintained when the machines stopped. In order to overcome these disadvantages, many improvement works have been done [11-14].

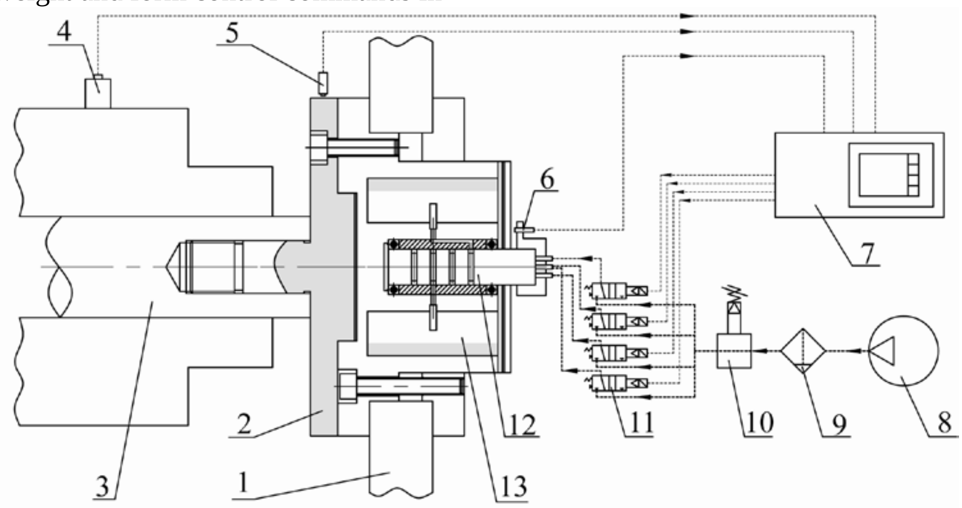
Different with the passive balancing, the active balancing requires an extra controller to form commands. Many studies have been performed on the advanced control methods [15-29]. For the active balancing controller, two major methods are used to determine the position of initial unbalance: optional control method and influence coefficient method. The former utilizes trial action of whole cycle or several positions to find the final solution, while the latter calculates the correction mass using influence coefficient before balancing [30-32]. After that, the optimization of control path is also important to minimize the balancing time and reduce unbalance response effectively [33].

In this study, we proposed a new type of liquid active balancing device in which compressed air is used for driving the balancing liquid to transfer between opposite chambers. Due to different requirements of installation, two specific structures were described in Section 2: one can be mounted in the middle of rotor and the other can be mounted at one end. The target control method utilizing influence coefficients was used to calculate compensation weight and form control commands in Section 3. In order to find the optimal control path, simulations on several paths were also done. In addition, we performed balancing experiments on two test rigs without stopping the machines in Section 4.

2 System design

The balancing device introduced in this paper is one of the liquid- transfer balancing devices. The power source of liquid transfer in the device is compressed air, so the device is known as Liquid-transfer automatic balancing device driven by compressed air. The system block diagram of the device is shown in Fig.1, and its working principle is as follows: a displacement sensor and a speed sensor are fitted above the rotor to detect the amplitude and phase of unbalance vibration; only when the synchronous vibration amplitude is higher than the limiting value, the control unit starts working; according to these two parameters, the control unit determines the correction weight of rotor and sends control commands to the solenoid valves in valve block; compressed air is then led to the required chamber by the gas channels in the device, and the liquid in corresponding chamber is driven to its opposite chamber; through the liquid transfer between opposite chambers, the liquid distribution is changed and a compensation weight is produced to balance the rotor. In the balancing system, an air compressor is needed to work as air source. An air filter and a pressure reducing valve are also needed to adjust the compressed air.

In the balancing system, balancing actuator is a core component which is comprised by balancing disc and air distributor.



1. Counterweight wheel 2. Connecting flange 3. Drive shaft 4. Acceleration sensor 5. Displacement sensor 6. Speed sensor 7.Control unit 8. Air source 9. Air filter 10. Pressure reducing valve 11. Electromagnetic valve block 12. Air distributor 13. Balancing disc

Fig.1 Principle diagram of balancing system

The balancing disc is mounted on the rotor and corotates with the rotor. Shown in Fig. 2, balancing disc includes four chambers, substantially disposed at equal angular intervals, for containing the balancing liquid which has been infused before the device starts up. At the bottom of these chambers, there are two liquid tubes, each connecting two opposite chambers. The two ends of each connecting tube are at the maximum radius of the chambers so as to immerse in the balancing liquid during the rotation of the rotor. In this way, compressed air is also prevented from entering the connecting tube. Each connecting tube extends on a decreasing radius of curvature from one end to the centre of the tube. This uses centrifugal force during rotation to prevent the balancing liquid in the tube from transferring into the chamber at the other end of the tube, so the centre of the tube must be lower than the liquid level of both chambers. In addition, the balancing disc also includes four gas tubes for supplying compressed air to the chambers. When the compressed air is led to one chamber, the pressure of the chamber rises gradually. When the pressure is high enough to overcome the centrifugal force, the balancing liquid is transferred to the diametrically opposite chamber through the connecting tube.

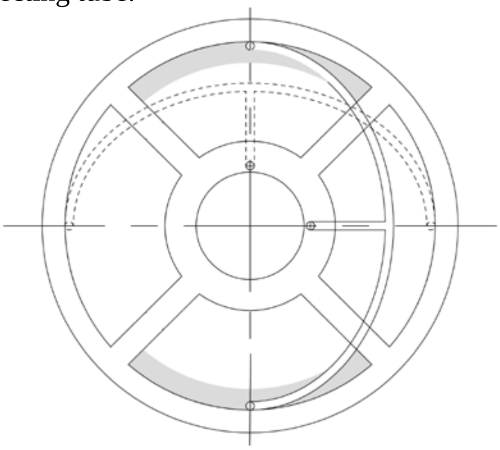
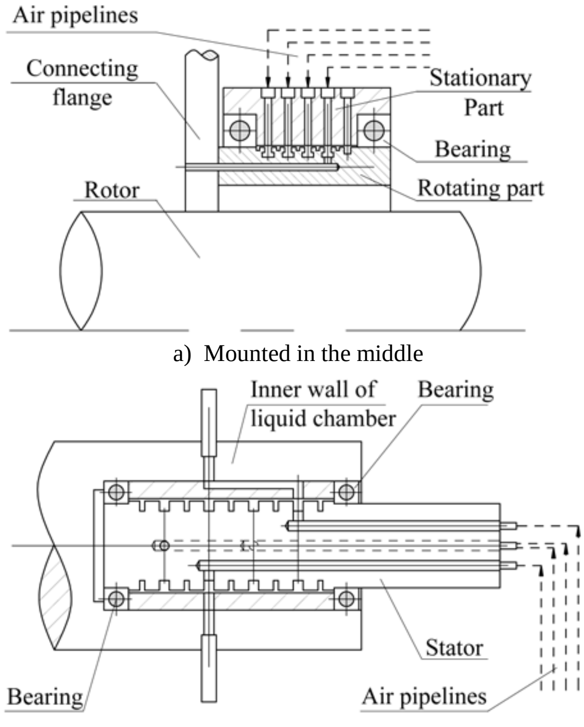


Fig.2 Schematic diagram of balancing disc

The air distributor is used to deliver air from the stationary air pipelines to the rotating balancing disc and consists of a stationary part, a rotating part and two ball bearings. The stationary part is connected with air pipelines and the rotating part is connected with balancing disc. For the mating surfaces of these two parts, there is at least one surface which has annular grooves to transfer compressed air. The stationary and rotating parts are separated by an air gap which should be as small as possible without allowing frictional contact between them during machine operation. More particularly, this air gap should be about dozens of microns. Two ball bearings are required to ensure the long-term operation of the air distributor in such a small gap. The stator cannot corotate with the balancing disc, but it can move with the balancing disc in other directions. Owing to the soft support of the stator, the bearings only bear the gravity and the harmonic vibration force of the stator, which makes the bearings have a long service life.



a) Mounted in the middle

b) Mounted at the end

Fig.3 Structure drawings of air distributor

According to the different requirements of installation site, the balancing actuator can be divided into two specific structures: one can be mounted in the middle of the rotor and the other can mounted at the two ends. Their differences are mainly in air distributor, shown in Fig.3. For the air distributor mounted in the middle, its outer ring is a stationary part used to install air pipelines and inner ring is a rotating part corotating with the rotor. Compared with this structure, the structure mounted at two ends is simpler: its rotating part is integrated into the inner wall of the liquid chamber and only a middle stator is needed.

3 Control strategy

In order to control the balancing actuator, a target control method is proposed to calculate the compensation weight and form the control commands. The method has three main features: 1) before the balancing actuator starts working, the control unit has already determined the amount and phase of the unbalance; 2) during the balancing process, the gas injection operation has a definite target; 3) during the balancing process, the vibration amplitude of the rotor decreases monotonically and there is no misadjustment phenomenon. The circular flow diagram is shown in Fig.4.

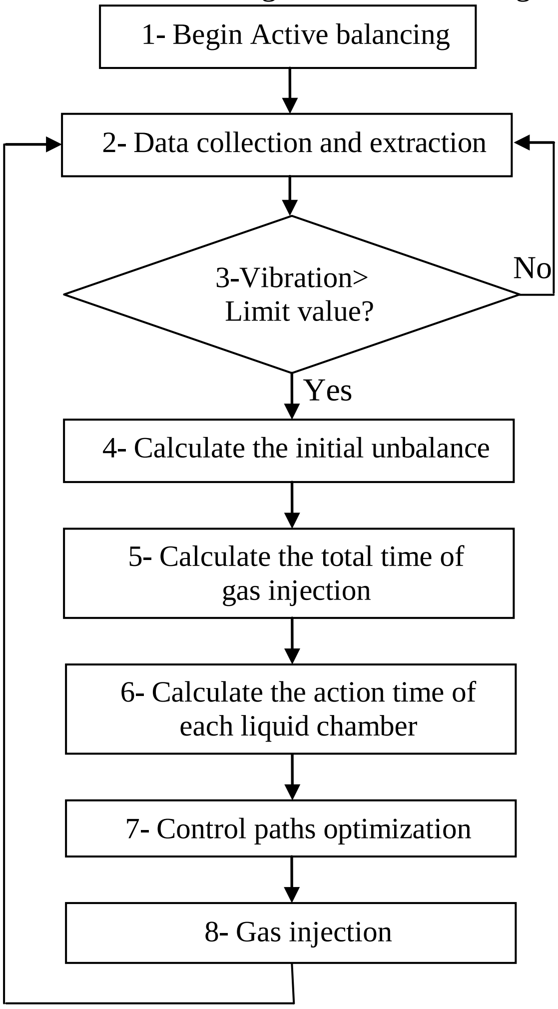


Fig.4 Circular flow-diagram of balancing system

3.1 Basic principle

The target control method can be divided into five parts:

1) Data collection and extraction. This part is used to receive the real-time vibration signals of detected device and extract synchronous component induced by unbalance. For the extraction process, there are several common methods, such as Tracking filter method and FFT method.

2) Target determination. From the synchronous vibration signal, influence coefficient method is used to calculate the amount and phase of the initial unbalance which is the balancing target, and the influence coefficients representing the relationship between vibration and unbalance are entered into the control unit in advance.

3) Transition. In this part, the amount of unbalance is converted to the total time of gas injection. The transition method can be Proportion Coefficient method or Adaptive control method.

4) Distribution. According to the phase of unbalance, the total time is distributed to the corresponding chambers. That is to say, the action time of each solenoid valve corresponding to one liquid chamber can be got through this part.

5) Command formation. The action time of these four solenoid valves in valve block are combined in a fixed order to form the control command, and the order will be discussed in the next section.

3.2 Data extraction

When the vibration signal passes through digital filter, part of the signal distortion and a time delay will happen, which definitely causes error for measuring results. In order to extract the vibration phase accurately, Tracking Filter method is used to process the vibration signal in this system. The initial vibration signal is written as follows:

$$x(t) = A_0 \cos(\omega_0 t - \varphi_0) + \sum_{i=1}^{N} A_i \cos(\omega_i t - \varphi_i) \quad (1)$$

where ω_0 is the working speed of the detected machines.

The control program provides two orthogonal sinusoidal signals y_1 and y_2 to multiply the vibration signal separately. The frequency of the two signals is equal to the working speed, so they can be written as,

$$y_1(t) = \sin(\omega_0 t) \quad (2)$$

$$y_2(t) = \cos(\omega_0 t) \quad (3)$$

Multiplying Eq. (1) by Eq. (2) gives,

$$\begin{aligned} x(t)y_1(t) = &\frac{1}{2}A_0 \sin\varphi_0 + \frac{1}{2}A_0 \sin(2\omega_0 t - \varphi_0) \\ &+\frac{1}{2}\sum_{i=1}^{N} A_i \sin\left[(\omega_0 + \omega_i)t - \varphi_i\right] \quad (4) \\ &+\frac{1}{2}\sum_{i=1}^{N} A_i \sin\left[(\omega_0 + \omega_i)t + \varphi_i\right] \end{aligned}$$

Similarly, multiplying Eq. (1) by Eq. (3) gives

$$x(t)y_2(t) = \frac{1}{2}A_0\cos\varphi_0 + \frac{1}{2}A_0\cos(2\omega_0 t - \varphi_0) + \frac{1}{2}\sum_{i=1}^{N}A_i\cos\left[(\omega_0+\omega_i)t-\varphi_i\right] + \frac{1}{2}\sum_{i=1}^{N}A_i\cos\left[(\omega_0+\omega_i)t+\varphi_i\right] \quad (5)$$

Through a low pass filter, two DC components can be extracted as,

$$V_x = \frac{1}{2}A_0\sin\varphi_0 \; V_y = \frac{1}{2}A_0\cos\varphi_0 \quad (6)$$

Therefore, the amplitude and phase of unbalance vibration can be given by,

$$V_0 = 2\sqrt{V_x^2+V_y^2}\ ;\ \ \varphi_0 = \arctan(V_x / V_y) \quad (7)$$

3.3 Calculation of action time

According to influence coefficient method, the relationship between the initial unbalance vibration signal $\vec{V}_0$ and the unbalance vector $\vec{U}_0$ of the detected device before balancing can be defined as,

$$\vec{V}_0 = \vec{K}\cdot\vec{U}_0 \quad (8)$$

Similarly, the unbalance response after balancing is given by,

$$\vec{V}_1 = \vec{K}\cdot(\vec{U}_0+\vec{U}_1) \quad (9)$$

where $\vec{U}_1$ is the correction mass vector formed by the balancing actuator after balancing.

Subtracting Eq. (8) from Eq. (9) gives

$$\vec{V}_1 - \vec{V}_0 = \vec{K}\cdot\left\{(\vec{U}_0+\vec{U}_1)-\vec{U}_0\right\} \quad (10)$$

The key of balancing is to find correction mass vector that makes the response zero after balancing. Hence, the correction vector can be

$$\vec{U}_1 = -\vec{K}^{-1}\cdot\vec{V}_0 = U\angle\theta \quad (11)$$

where U and β are the amplitude and phase of correction mass vector, respectively.

If the balancing ability formed by a unit mass of balancing liquid is represented as k, the mass of balancing liquid transferred by compressed air can be represented as,

$$\vec{M} = m\angle\theta = (U/k)\angle\theta \quad (12)$$

During the transfer process, the mass flow rate q in the connecting tube of two opposite chambers can be considered as a constant. Therefore, the total time of gas injection T can be written as,

$$T = m/q = U/qk \quad (13)$$

For the balancing device proposed in this paper, if compressed air is injected to one chamber, a correction vector is formed in its opposite chamber. The phase of gas injection ψ is defined by,

$$\psi = \theta + 180 \quad (14)$$

According to sine or cosine theorem, the total time is resolved to these four chambers and the open time of each solenoid valve is confirmed.

3.4 Control paths optimization

During the resolving process of gas injection time, there are several cases: 1) when the phase of gas injection is at 0, 90, 180 or 270 degree, the balancing device only needs to inject gas to one chamber; 2) when the phase of gas injection is at 45, 135, 225 or 315 degree, the balancing device needs to inject gas to two neighbouring chambers simultaneously, and the gas injection times of these two chambers are also equal; 3) when the phase of gas injection is at other positions, the balancing device needs to inject gas to two chambers, but these two chambers have different times. For the case 3), we should consider the gas injection order of these two chambers and choose one control path in which the unbalance response can be reduced quickly.

In order to compare the control results of different control paths, we take the gas injection phase $(45<\psi<90)$ for example.

Assuming that the initial unbalance mass is m and its phase is β which is equal to gas injection phase, we resolve the initial unbalance vector to the real and imaginary axis and the process can be written as,

$$\vec{M} = m\angle\beta = m\cos\beta + i\cdot(m\sin\beta) \quad (15)$$

where $\beta=\psi$, and $45<\beta<90$.

In this case, compressed air is delivered to Chamber A and B. The mass flows q in these two connecting tubes are equal, and the gas injection time of Chamber A and B can be written as,

$$t_a = m\cos\beta/q \ ,\ t_b = m\sin\beta/q \quad (16)$$

where $t_b > t_a > 0$, which means that the time of Chamber B is longer than that of chamber A.

In this case, there are five control paths for different gas injection order:

(1) Open the solenoid valve of chamber B firstly, and the solenoid valve of chamber A does not begin to work till the gas injection of chamber B is finished. So the balancing process is divided into two parts, and the residual unbalance can be represented as,

$$m_{rest}=\begin{cases}(m\cos\beta)+i\cdot(m\sin\beta-2tq) & (0\le t\le t_b)\\(m\cos\beta-2(t-t_b)q)+i\cdot(m\sin\beta-2t_bq) & (t_b<t\le t_a+t_b)\end{cases}\tag{17}$$

(2) Open the solenoid valve of chamber A firstly, and the solenoid valve of chamber B does not begin to work till the gas injection of chamber A is finished. The balancing process is also divided into two parts, and the residual unbalance can be represented as,

$$m_{rest}=\begin{cases}(m\cos\beta-2tq)+i\cdot(m\sin\beta) & (0\le t\le t_a)\\(m\cos\beta-2t_aq)+i\cdot(m\sin\beta-2(t-t_a)q) & (t_a<t\le t_a+t_b)\end{cases}\tag{18}$$

(3) Open the solenoid valves of chamber A and B at the same time. When the gas injection of chamber A is finished, its corresponding solenoid valve is closed, but the solenoid valve of chamber B is still open until its gas injection is also finished. During the balancing process, the residual unbalance can be represented as,

$$m_{rest}=\begin{cases}(m\cos\beta-2tq)+i\cdot(m\sin\beta-2tq) & (0\le t\le t_a)\\(m\cos\beta-2t_aq)+i\cdot(m\sin\beta-2tq) & (t_a<t\le t_b)\end{cases}\tag{19}$$

(4) Open the solenoid valve of chamber B firstly. After a little while, the solenoid valve of chamber A is also open, and these two solenoid valves are closed at the same time. During the balancing process, the residual unbalance can be represented as,

$$m_{rest}=\begin{cases}(m\cos\beta)+i\cdot(m\sin\beta-2tq) & (0\le t\le t_b-t_a)\\(m\cos\beta-2(t-(t_b-t_a))q)+i\cdot(m\sin\beta-2tq) & (t_b-t_a<t\le t_b)\end{cases}\tag{20}$$

(5) The gas injection time of chamber A is divided into several parts. During the gas injection process of chamber B, open the solenoid valve of chamber A discontinuously. If the time of chamber A is divided into j parts, the balancing process is divided into 2j parts and the residual unbalance can be represented as,

$$m_{rest}=\begin{Bmatrix}(m\cos\beta) & +i\cdot(m\sin\beta-2tq) & (0\le t\le(t_a-t_b)/j)\\(m\cos\beta-2(t-(t_a-t_b)/j)q) & +i\cdot(m\sin\beta-2tq) & ((t_a-t_b)/j<t\le t_a/j)\\(m\cos\beta-2t_bq/j) & +i\cdot(m\sin\beta-2tq) & (t_a/j<t\le(2t_a-t_b)/j)\\(m\cos\beta-2(t-2(t_a-t_b)/j)q) & +i\cdot(m\sin\beta-2tq) & ((2t_a-t_b)/j<t\le 2t_a/j)\\ & \cdots & \cdots\\(m\cos\beta-2(j-1)t_bq/j) & +i\cdot(m\sin\beta-2tq) & ((j-1)t_a/j<t\le(jt_a-t_b)/j)\\(m\cos\beta-2(t-j(t_a-t_b)/j)q) & +i\cdot(m\sin\beta-2tq) & ((jt_a-t_b)/j<t\le t_a)\end{Bmatrix}_{2j\times1}\tag{21}$$

For example, $m\cos\beta=10\,(g)$, $m\sin\beta=20\,(g)$, $q=2\,(g/s)$. In this situation, $t_a=2.5\,(s)$, $t_b=5\,(s)$. Utilizing Eq. (17) – (21), the change curve of residual unbalance for different control paths can be calculated, and the results are shown in Fig. 5.

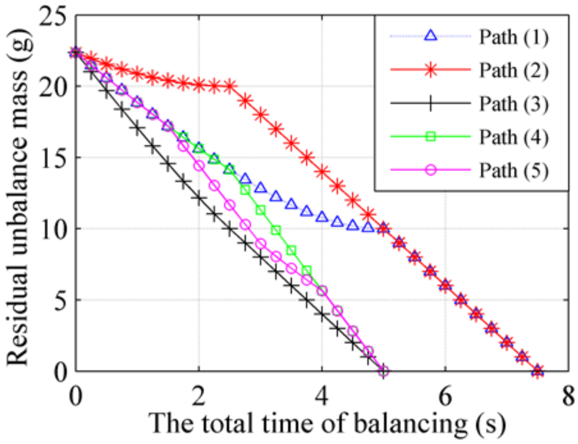


Fig.5 Comparison of control paths

Comparing these five control curves, the control speed and control effect of Path (3) are better than the others. So when the control unit forms the control command, it should follow Path (3) and the command formation is comprised by three steps: 1) open the solenoid valves of two targeting chambers simultaneously, 2) close the solenoid valve of one chamber, the time of which is shorter than the other, 3) close the other solenoid valve and the gas injection process is finished.

4 Balancing experiment

4.1 Balancing device mounted in the middle

The bench drilling machine is remodeled to build a vertical-type experimental setup, shown in Fig. 6. Its drill bit is the detected rotor, in the middle of which the active balancing device is mounted. Two eddy current sensors are used to measure the unbalance vibration of the drill bit.

The balancing disc and the inner ring of the air distributor are fixed to the rotor through a connecting flange which is welded to the drill bit. The outer ring of the air distributor stays still during operation and has four gas-type fittings, connected with four gas pipelines, to deliver compressed air to the inner ring and the balancing disc. The outer ring is fixed to the machine foundation through a soft method, that is to say, this method only limits its rotation, but does not limit its movements in other directions. This fixed mode reduces the operating load of bearings between the outer and inner rings greatly, which is good for a long service life.

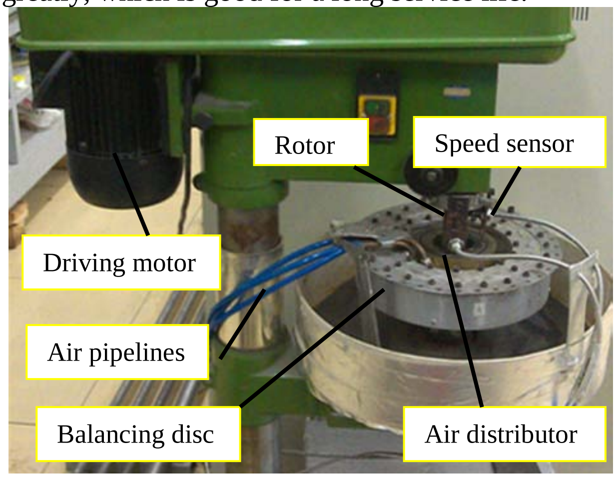


Fig.6 Experimental device of balancing system installed in the middle of rotor

The NI DAQ card PCI6220 and Digital I/O card PCI 6515 are adopted as the hardware module. In order to control the active balancing device automatically, we develop a data processing and active control program using the Labview software, shown in Fig.7. While the detected machine is running, the program always monitors the vibration status of the drill bit. Once the synchronous vibration amplitude is higher than the limiting value, the program sends out control command and the balancing actuator starts working. The compressed air used during active balancing is supplied by an oilless air compressor, and its air outlet pressure is set to 0.1 MPa.

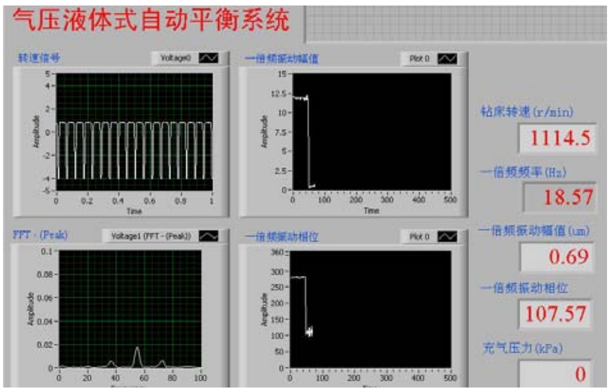


Fig.7 Data processing program using Labview

Limited by the running speed of bench drilling machine, a balancing experiment is performed at 1080 rpm, and the balancing result is shown in Fig. 8. After the rotor ran stably at the working speed, the amplitude of initial unbalance response was about 26.1 um peak-to-peak and the phase is 203 degree. The active balancing system was then started and the total gas injection time was about 5 seconds. The response decreased to 1.0 um peak-to-peak after balancing and the amount of vibration decreased by 96.2%. Restricted by the accuracy of the drilling machine, when the vibration amplitude was lower than 1.0 um, the phase of vibration fluctuated up and down between 220 degree and 150 degree, which affected the improvement of balancing accuracy. Even so, the result~~s~~ has already proved the availability of the proposed active balancing device.

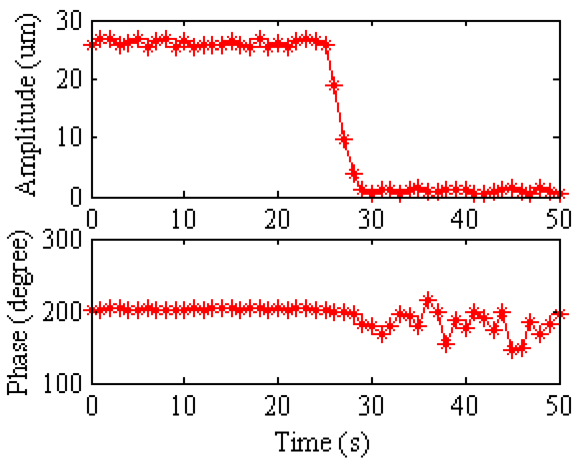


Fig.8 Balancing result of balancing system installed in the middle of rotor

4.2 Balancing device mounted at the end

The spindle system for cylindrical grinding machine, capable of mounting the active balancing device we proposed in this paper, is shown in Fig.9. Single plane balancing that uses one balancing device was performed, by aiming at the end of the spindle.

The counterweight wheel, which has the same geometrical dimensions as the standard grinding wheel and is installed to the spindle by two wheel flanges, is the vibration source of active balancing experiment. The balancing disc of balancing actuator is integrated into one wheel flange, which is quite near the vibration source and good for active balancing. The structure of the air distributor is simplified, which only need one still stator in the centre hole of the balancing disc. In the stator, there are four axial gas channels which are connected to four air pipelines and used to deliver compressed air to the balancing disc. Two ball bearings are required to ensure the running clearance between the stator and balancing disc. The stator cannot corotate with the balancing disc, but it can move with the balancing disc in other directions. Owing to the soft support of the stator, the bearings only bear the gravity and the harmonic vibration force of the stator, which are about dozens of N. Compared with the limit load of these bearings, which is more than 2000 N, the operating load is quite small. The air source, the valve block and the control unit are the same with the devices used in the vertical-type experimental setup, but the air outlet pressure is set to 0.3 MPa.

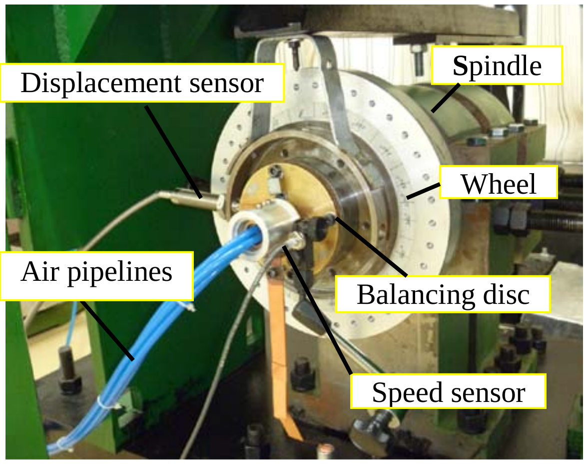


Fig.9 Experimental device of balancing system installed at the end of rotor

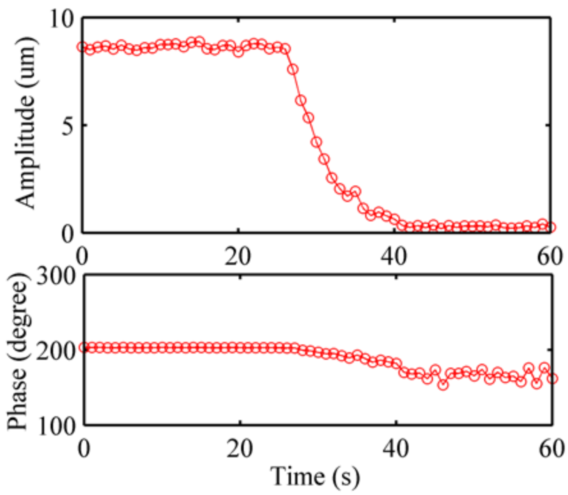


Fig.10 Balancing result of balancing system installed at the end of rotor

The balancing experiment is performed at 5000 rpm, and the balancing result is shown in Fig. 10. After the rotor ran stably at the balancing speed, the amplitude of initial unbalance response was 8.6 um peak-to-peak and the phase was 200 degree. The active balancing system was then started and the total gas injection time was about 15 seconds. The response decreased to 0.3 um peak-to-peak after balancing and the amount of vibration decreased by 96.5%. Due to the small value of vibration amplitude, the phase of vibration was no longer a fixed value, but fluctuated between 150 degree and 170 degree.

5 Conclusion

In this paper, we propose a liquid active balancing device which can be mounted both in the middle and at one end of the rotor. We provided a target control method in which the gas injection target has already confirmed before balancing and the unbalance response of rotor decreases monotonically during balancing process.

Different control paths would generate different balancing effects, so simulations on several control paths were done to find the optimal solution. The chosen control path is as follows: when compressed air needs to be injected into two chambers, the solenoid valves of the two target chambers should be open at the same time; when the gas injection of one chamber is finished, its corresponding solenoid valve is closed, but the solenoid valve of the other chamber is still open until its gas injection is also finished.

Based on the target control method, active balancing works were also carried out on two experimental setups. The results showed that both of the two active balancing devices could reduce the unbalance response by more than 90% within 15 s, which verified the feasibility and availability of the balancing devices.

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