Study on Moving Strategy of Internal Mechanical On-Line Balancing System

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Abstract. Mechanical balancing system driven by the motor can cause wrong adjustment and long balancing time in the controlling process, which will result in lower accuracy of rotation. In order to solve this problem and achieve more efficient online dynamic balance, the optimal moving path of the built-in mass block of balancing device can be determined by us. Four kinds of moving paths for mass block are designed by using for balancing to make experimental verification of spindle dynamic balance movement. By comparing experimental results of balance accuracy and balance efficiency, the optimal dynamic balancing strategy is determined. The results show that the designed moving strategy is reasonable, and the moving optimized path can carry out more accurate control precision and shorter adjustment time to achieve the expected effect. The better control strategy of dynamic balance lays the foundation for the high-precision operation of the spindle system.

1. Introduction

The cause of the vibration of the mechanical spindle is caused by the manufacturing, the installation technology, wear down, and impact during the operation and so on[1]. The statistics show that the vibration caused equipment failure to account for 60%-70%[2]. In rotating machinery, vibration caused by mass unbalance weigh heavily. In order to reduce the effect of vibration on the spindle, the application of on-line balance technology plays an important role in solving the vibration caused by mass unbalance of the spindle and so on[3-4], the mass imbalance affects production quality, accelerates wear of spindle and bearing, and reduces service life of equipment[5]. There is lots of random imbalance in the imbalance of high speed rotating machinery. We usually adopt online dynamic balancing device to control imbalance of the machinery[6-7].

Li Yong proposed a permanent magnet differential frequency electric balancing head, which consisted of two removable cars as two counterweight[8]. The balancing device used a motor to drive the counterweight, focusing more on structure and drove weight block. Gao Jinji and Chen Lifang researched on magnetic-driven bi-disc balancer[9]. First of all, they analyzed the problems of an existing motor-driven bi-disc balancer, namely the error movement, vibration and the long time needed to achieve balancing, and proposed solutions which were employed in the design of a new magnetic-driven bi-disc balancer. The optimal movement principles, methods of their determination and bi-disc error-free movement control algorithm had been obtained to improve the automatic balance quality effectively and achieve the error free. All of the above studies are focused on a certain direction or under certain conditions.

Abroad is more advanced in the research of balance device. HM and HS series of dynamic balancing machine made by Schenck Process Gmb H could reduce the unbalance of 95%[10]. ST
balance head from Italy MARPOSS company, working speed 1100~6500r/min, balance capacity 400~13000g.cm\cite{11}. The US LORD Electromanetic Drive Balance System could achieve balance only after 1.5s auto-adjustment. Kennametal’s automatic balancing system made the spindle rotation accuracy within 50μm in two seconds\cite{12}.

In this paper, on the basis of previous researches on mass block moving strategy, we carried out online dynamic balancing control experiments for several different mass block moving paths, and determined the optimal mass block mobility plan.

2. Mass block mobile strategy

2.1. balancing principle

In order to simplify the expression, the two weight block were equivalent to two mass points on the same radius, further then balance mechanical model of double mass block is established as shown in Figure 1. The initial positions of mass blocks A and B are in the three quadrant 225° and the four quadrant 340°, angle between initial unbalance of the spindle and horizontal line is 130°.

Inherent unbalance force of the system, centrifugal force of weight block and residual unbalance force of the system exist in the balance system in a measurement and control period. Unbalances which include the size and phase of inherent unbalance force of the system can be tested for testing equipment at any time. The two mass blocks with equal mass on the rotation radius of the same plane only need to move to the opposite direction of the inherent imbalances in the shortest time, and then resultant force of centrifugal force caused by two mass block is equal to the inherent imbalance force, and the imbalance is offset, spindle vibration caused by mass unbalances is controlled.

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos(\frac{19\pi}{36} - \frac{\pi}{36} - t), \ 0 \leq t \leq 5 \] \hspace{1cm} (1)

2.2. moving path

The initial unbalance of the spindle was \( M \), which represented the inherent imbalance of the spindle. \( m_1 \) and \( m_2 \) represented two mass blocks on the balance head respectively. The moving speed of mass block was 5°/s, let time \( t \) act as variable. \( P \) which represents resultant force was calculated using cosine theorem, and then, two force balance between the calculated resultant force and the inherent unbalance force could be obtained. The path of the mass block moves is as follows:

Path 1: The B mass block was moved first, when the B mass block moved to the end, the A mass block would be moved until the end. Rational calculation formula is as follows:

Figure 1. Two mass block moving model
\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{\pi}{36} t + \frac{9\pi}{36}\right), \quad 5 \leq t \leq 21 \]  
(2)

Path 2: The A mass block was moved first, when the A mass block moved to the end, the B mass block would be moved until the end. Rational calculation formula is as follows:

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{\pi}{36} t + \frac{19\pi}{36}\right), \quad 0 \leq t \leq 16 \]  
(3)

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{5\pi}{4} - \frac{\pi}{36} t\right), \quad 16 \leq t \leq 21 \]  
(4)

Path 3: A mass block and B mass block were moved simultaneously, the A mass block reached the predetermined location first, and the B mass block continued to move until the end. Rational calculation formula is as follows:

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{19\pi}{36}\right), \quad 0 \leq t \leq 5 \]  
(5)

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{14\pi}{36}\right), \quad 5 \leq t \leq 21 \]  
(6)

Path 4: The B mass block was moved first, after a period of time, the A mass block was moved, then, the two mass blocks would reach predetermined position at the same time. Rational calculation formula is as follows:

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{19\pi}{36}\right), \quad 0 \leq t \leq 15 \]  
(7)

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{17\pi}{18}\right), \quad 15 \leq t \leq 18 \]  
(8)

\[ p^2(t) = m_1^2 + m_2^2 - 2m_1m_2 \cos\left(\frac{35\pi}{18} - \frac{\pi}{18} t\right), \quad 18 \leq t \leq 21 \]  
(9)

3. Experimental Research

3.1. Platform building

Motor driven mechanical on-line automatic balancing system was researched in this paper, as shown in Figure 2. Compared with other balancing devices, it with simple structure, small size and light in weight is suitable for high speed operating conditions. It has two micro motors inside, the two micro motor are connected with control system by brush and slip ring to achieve rotation and angle instruction. In order to realize on-line balancing of rotor, precision gearing system drove by micro motors drives two mass blocks to move in radial direction until reaching the set of target value of the vibration.

Experimental device consists of a motor, a spindle, a computer control unit, vibration sensors, balance device, and so on. Computer passes control command to control device to control the speed of the micro motor in the balance head; sensor is connected to the spindle housing, and detects spindle speed pulse signal to transmit control unit, which generates a signal to adjust mass blocks of the balance head, and imbalance of the spindle is eliminated quickly. The experimental platform is shown in Figure 3.

3.2. control experiment

Online automatic balancing experiment was carried out on the spindle at four operating speeds of 2000r/min, 2500r/min, 3000r/min and 3500r/min. Because the balancing device was inside the spindle, the moving location of mass block couldn’t be detected in real-time in the balancing process, so relationship between mass block, residual force and vibration amplitude couldn’t be obtained. Based on data of vibration amplitude acquired in auto-balancing experiments, moving paths could be summarized and applied to balance experiments by manual adjustment. The process was used to check
the reasonableness of the mass block moving path of the balancing device, and the results of the balance were compared to each other to select optimal moving path.

Balance parameters obtained at four different working speeds were shown in Table 1. It could be seen from the table that the initial amplitude of vibration under 2000r/min was 6.24μm, after the on-line dynamic balance, amplitude decreases gradually, and final average amplitude was 1.18μm. Initial amplitude of vibration under 2500r/min was 8.18μm, and average amplitude of the dynamic balance was 1.54μm after on-line dynamic balance. Initial amplitude of vibration under 3000r/min was 9.51μm, and average amplitude of the dynamic balance was 1.85μm after on-line dynamic balance. Initial amplitude of vibration under 3500r/min was 11.35μm, and average amplitude of the dynamic balance was 2.76μm after on-line dynamic balance. The experimental results showed that vibration of the mechanical spindle was effectively suppressed at working speed, and amplitudes were obviously reduced. Compared with the dynamic balancing effect under different speeds, the balance efficiency would decrease with the increase of speed. It was obvious that the effect of influence coefficient method was ideal in the process of single plane dynamic, and performance parameters meet the requirements.

### Table 1. Balance parameters at different working speeds

| Spindle Speed (r/min) | 2000   | 2500   | 3000   | 3500   |
|----------------------|--------|--------|--------|--------|
| Initial Imbalances   | 6.16μm | 8.25μm | 9.52μm | 10.79μm|
| Trial Weight (g)     | 10g    | 11g    | 12g    | 13g    |
| Unbalance after Trial| 7.78μm | 9.72μm | 10.38μm| 13.45μm|
| Correction Weight (g)| 10.5g  | 11.6g  | 13.6g  | 13.8g  |
| Residual Unbalance    | 1.21μm | 1.55μm | 1.77μm | 2.82μm |
| Influence Coefficient | 0.00981 μm/(g·mm)  | 0.0116 μm/(g·mm)  | 0.0121 μm/(g·mm)  | 0.0136 μm/(g·mm)  |
| Balance Efficiency    | 80.35% | 81.21% | 81.41% | 73.86% |

### 3.3. Analysis of Experimental Results

A maximum vibration amplitude was set at different speeds in the process of experiment. When vibration amplitude exceeded the set value, controller would output control instructions, and then the spindle would be balanced in manual mode. The selected speeds were 2000r/min, 2500r/min, 3000r/min and 3500r/min respectively.

At the speed of 2000r/min, the initial vibration peak value was 6.35μm, the vibration peak value was reduced to 1.04μm after manual balancing. The proportion of amplitude drop was 83.62%. At the speed of 2500r/min, the initial vibration peak value was 8.24μm, the vibration peak value was reduced to 1.42μm after manual balancing. The proportion of amplitude drop was 82.76%. At the speed of 3000r/min, the initial vibration peak value was 9.72μm, the vibration peak value was reduced to 2.45μm after manual balancing. The proportion of amplitude drop was 74.79%. At the speed of
3500r/min, the initial vibration peak value was 12.34μm, the vibration peak value was reduced to 2.52μm after manual balancing. The proportion of amplitude drop was 79.57%. The relationship between amplitude of vibration at different speeds and moving path of mass blocks before and after balancing from experiment was shown in Figure 4. At the speed of 2500r/min, the relationship between vibration amplitude in a different paths and moving path of mass blocks was shown in Figure 5. Under simulated condition, the path 3 was optimum path, in which two mass blocks were moved simultaneously at first. One of mass blocks would reach the predetermined position first than the other mass block, so that the amplitude dropped slowly at first and then dropped faster. When all two mass blocks reached the predetermined position, the residual force of the spindle would be minimized and the amplitude would decrease greatly.

![Figure 4. Relationship diagram between amplitude and number of mobile steps at different rotational speeds](image)

![Figure 5. relationship diagram between amplitude and different path](image)

Through the above experimental results, it was concluded that vibration amplitude of online manual balancing of the spindle decreased obviously, which was close to the online dynamic balancing, and the design of mobile strategy was reasonable, so as to achieve the desired effect.

4. Conclusion
Through the study of the mechanical balance device of double balance block mobile strategy, it is found that factors affecting the balance effect of spindle are different start and end time, different orders and different directions in the process of mass block movement. Choosing a suitable moving path can improve the balance efficiency of the spindle, there is great significance to balance spindle fast and efficiently while machine tools are working in complex conditions. Study of moving strategy of mass blocks in balancing device has played a significant role in achieving high efficient online
dynamic balance. Through experiments, the feasibility and accuracy of mass blocks moving path is verified, and the best mobile strategy of mass blocks is selected, which solves the problems of error movement, vibration and the long time needed to achieve balancing.

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