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Design and experimental study of active balancing actuator driven by ultrasonic motor①

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Abstract

The on-line active balancing system can suppress the vibration caused by unbalance of rotating equipment in real time, and is of great strategic significance for high-end equipment in machining, aviation and other fields. As the core equipment of the on-line active balancing system, the performance parameters of the active balancing actuator determine the overall performance of the balancing system. The balancing method of the existing mechanical balancing actuator is improved, and a new active balancing actuator structure based on ultrasonic motor is proposed. The stress distribution of the actuator is analyzed by establishing a three-dimensional model of the actuator. The feasibility and effectiveness of the above structure are verified by the experimental research on the grinder. The results show that the active balancing actuator based on ultrasonic motor can drive the counterweight to complete the required self-locking and stepping actions in the whole cycle. The structural design scheme is feasible. At the same time, it also shows that the actuator can suppress the unbalance vibration of the grinder. The active balancing actuator based on ultrasonic motor drive studied in this paper lays a foundation for the industrial application of this kind of actuator in the future.

Key words: active balancing, unbalance vibration control, ultrasonic motor

0 Introduction

In modern industry, mechanical vibration is a major obstacle to the development of rotating machinery. Excessive vibration caused by rotor imbalance is one of the most common faults of rotating machinery, which seriously affects the operation efficiency, working accuracy and service life of equipment[1]. The active balancing actuator can actively reduce the unbalance vibration during operation without shutdown and manual intervention, and the balancing speed is fast, which is considered to be an effective method to solve the unbalance vibration of rotating machinery. At present, it has achieved good engineering application in high-end machine tools and aero-engine[2-4]. The active balancing system is mainly composed of sensors (detecting rotating speed and vibration amplitude of rotating equipment), controllers (signal processing and output), balancing actuator (reducing vibration amplitude of equipment) and related accessories. As the final actuator of the whole system, the balancing actuator has always been the key research object in this field in China and abroad[5]. According to the different ways of changing the rotor mass distribution inside the actuator, the active online balancing actuator can be divided into three types: motor type[6], liquid type[7-9] and electromagnetic type[10-12].

The motor type active balancing actuator has the advantages of easy installation, no complex auxiliary device, simple operation, fast balancing speed and high balancing accuracy. The rotor can be balanced online by reducing or increasing the correction quality in the appropriate position of the rotor in operation. At present, the main motor-type active balancing actuators on the market are mostly driven by complex mechanical structures to reach the designated position to suppress the unbalance vibration of the equipment. Although this method can achieve the effect of vibration suppression, due to the meshing of complex gears and worms, the whole device is complex, difficult to manufacture and assemble, and difficult to maintain in the later

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stage[13-14]. Therefore, this paper introduces a new type of active balancing actuator driven by ultrasonic motor, which effectively avoids the mechanical transmission chain such as gear and worm, greatly reduces the difficulty of manufacturing and assembly, and verifies its feasibility through experiments.

1 Fundamental principle

The active balancing actuator studied in this paper is the balancing mode of double counterweights balancing, and its principle is shown in Fig. 1. The vibration sensor (acceleration sensor) is used to collect the vibration amplitude of the rotating equipment, and the positioning sensor is used to determine the position of the counterweight; key-phase sensor is used to collect rotational speed information of rotating equipment.

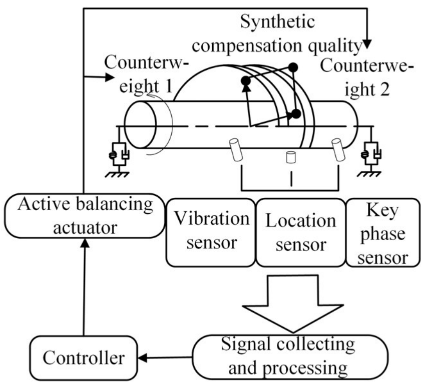
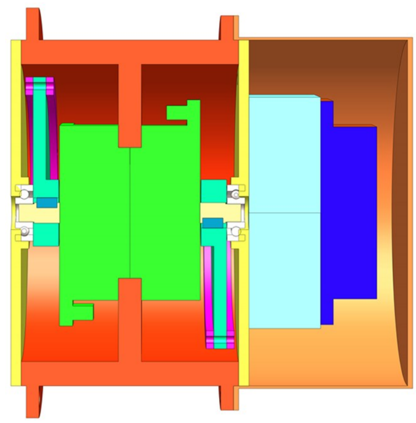


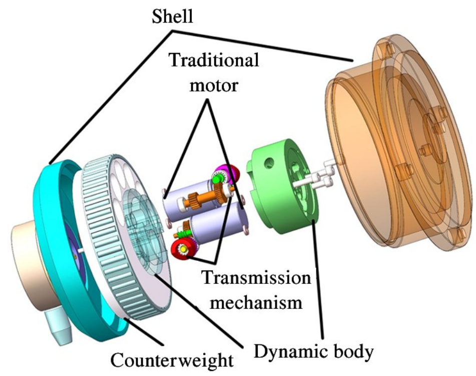
Fig. 1 Balance principle of double counterweights

The collected signals are processed by the National Instruments (NI) board and passed to the controller, personal computer (PC) terminal, and then the instructions are sent to the ultrasonic motor inside the active balancing actuator. To suppress the unbalance vibration of rotating equipment, the ultrasonic motor is used to drive the counterweight to the designated position after calculation.

This article introduces a new type of active balancing actuator based on ultrasonic motor drive. The ultrasonic motor uses the inverse piezoelectric effect of the internal piezoelectric material to stimulate the micro vibration of the elastomer in the ultrasonic frequency band, and converts the friction between the stator and the rotor into the rotation of the rotor[15]. Therefore, the new type of active balancing actuator studied in this paper uses the above-mentioned working characteristics of the ultrasonic motor to realize the self-locking and driving of the counterweight. The specific working principle is as follows. When the mass distribution of the counterweight needs to be adjusted, the ultrasonic motor is powered, and the frictional force generated by the piezoelectric ceramic vibration in the ultrasonic motor drives the counterweight to rotate step by step to form the compensation quality required to suppress the unbalance vibration of the equipment; when the counterweight reaches the specified position, the power supply for the ultrasonic motor is stopped, and the stable self-locking of the counterweight position is realized through the friction torque generated between the stator and the rotor of the ultrasonic motor. The whole actuator has a simple structure and is easy to assemble and maintain. At the same time, the entire actuator uses infrared signals to receive instructions to control the internal ultrasonic motor to drive the special-shaped counterweight to reach the specified position and the combined compensation quality. Its structure is shown in Fig. 2.



(a) Active balancing actuator driven by ultrasonic motor



(b) Traditional mechanical active balancing actuator

Fig. 2 Structure diagram of active balancing actuator

Therefore, compared with the traditional motor-type balancing actuator, the active balancing actuator based on ultrasonic motor drive studied in this paper has the following advantages.

(1) With compact structure and large torque density (torque mass ratio), the torque mass ratio of the ultrasonic motor can reach 5 – 10 times that of the traditional electromagnetic motor, which helps to reduce

the axial size of the actuator[15].

(2) With low speed and large torque, direct drive can be realized without gear reduction mechanism. The structure is simple and easy to maintain in the later stage.

(3) The inertia of motor moving parts is small, which can achieve millisecond response speed. The position and velocity control precision is high, and the displacement resolution is high. The whole actuator can control the counterweight accurately to suppress the vibration of the equipment.

(4) The motor can be power-off self-locking, and has a large holding torque, so that the entire actuator does not need to use the worm structure to achieve self-locking.

(5) No magnetic field is produced and is not disturbed by external magnetic field. Taking into account the working environment of the actuator, when the piezoelectric material and friction material of the ultrasonic motor are properly selected, it can work in extreme environments such as vacuum, high/low temperature environment, which greatly improves the application range of the actuator.

2 Structure design

2.1 Design of actuator structure

Active balancing actuator is mainly composed of ultrasonic motor and special-shaped counterweight, in which the whole actuator rotates synchronously with the rotating equipment. The whole active balancing actuator is shown in Fig. 3. The whole device is arranged symmetrically with the shell ribs, so as not to affect the balance quality of the balance rotor itself. Two symmetrical ultrasonic motors are fixed on the shell rib plate[16]. When the ultrasonic motor receives the signal of the controller, the mass distribution inside the whole device is changed by controlling the position of the special-shaped counterweight, in order to suppress unbalance vibration of rotor on line. The special-shaped counterweight with the motor is made of brass, and the counterweight part with the shaft is strengthened. In order to make full use of the internal space of the actuator and improve the maximum quality of the balance, the whole counterweight is designed as a special-shaped structure. At the same time, the protruding part is connected to the main body through the sinker screw, which can be determined by the unbalance vibration value of the rotating equipment.

Whether the protruding part is installed or not can reduce the quality of the whole actuator. On the outside of the special-shaped counterweight, there are two supporting plates matching the shaft through the bearing. The supporting plate is made of aluminum alloy, so as to reduce the quality of the whole actuator. One side of the support plate is embedded in the flange plate of the grinder to protect the internal structure. The other side of the support plate is used as the installation deck of the ultrasonic motor controller, and also plays a protective role.

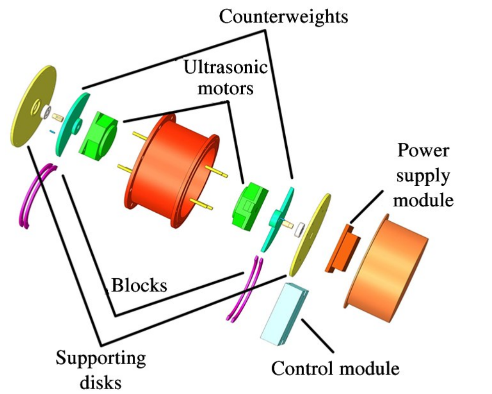


Fig. 3 Explosion diagram of active balancing actuator

2.2 Balance ability

The balance ability of the whole actuator depends on the structure and size of the counterweight. In this paper, the active balancing actuator based on ultrasonic motor is studied. In order to shorten the axial size and maximize the balance ability of the whole actuator, the counterweight is designed as a semi disc and a convex part. The two parts are connected by sink screw, as shown in Fig. 4. On the one hand to increase the balance ability of the entire actuator. On the other hand, when the required compensation mass is too small, the mass of the entire actuator can be reduced, and the influence on the spindle of the rotating equipment can be reduced. At the same time, the shaft hole with the motor shaft is strengthened, so that the structural strength of the whole counterweight is improved and the balance ability is guaranteed.

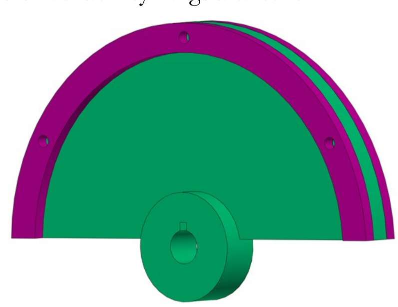


Fig. 4 Diagram of active balancing actuator counterweight and blocks

It can be seen from Fig. 5 that the initial unbalance mass of the rotor of the balancing rotating equipment is

$\boldsymbol{U}_0$. When the actuator accepts the instruction, the two disks begin to rotate gradually driven by the ultrasonic motor, so as to change the angle between the mass $\boldsymbol{U}_A$ and $\boldsymbol{U}_B$ of the counterweights on both sides. According to the parallelogram rule, the total compensation mass $\boldsymbol{U}_C$ of active balancing actuator increases with the decrease of angle φ. When the orientation of counterweights on both sides is the same and the angle is 0 °, the total equilibrium mass $\boldsymbol{U}_C$ reaches the maximum, namely the sum of $\boldsymbol{U}_A$ and $\boldsymbol{U}_B$. By changing the angles φ and φ_C, the equilibrium mass of the entire active balancing actuator increases from 0 to the maximum value of $\boldsymbol{U}_C$. Therefore, the maximum value of $\boldsymbol{U}_C$ is the balance ability of the actuator[2].

The balance ability of the counterweight can be expressed as

$$\boldsymbol{U} = mr = \rho B(R_2^3 - R_1^3)\sin \quad (1)$$

$$m = \rho B\theta(R_2^2 - R_1^2) \quad (2)$$

Among them, the overall material of the counterweight is brass alloy, and the density ρ is 0.0085 g/mm^3. The overall size of the counterweight is shown in Table 1. With Eq. (1) and Eq. (2), the balance ability of the whole actuator can be calculated to be 13 443.2 g · mm.

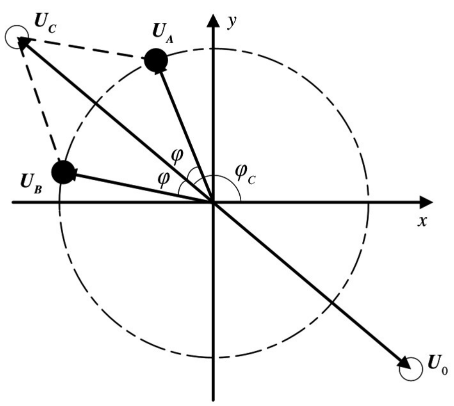


Fig. 5 Balance principle diagram of double counterweights

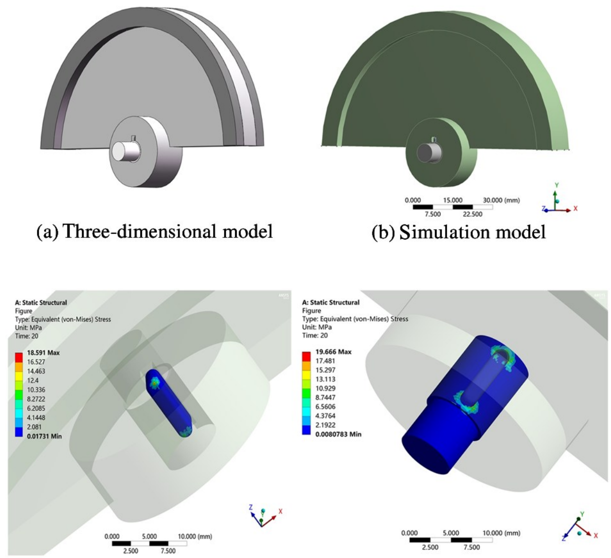
Table 1 Counterweight design

	Depth B /mm	Angle θ/rad	Inner diameter R_1/mm	Outer diameters R_2/mm
Main part	5	π	13	53
Protruding part	4	π	46	53

3 Structural simulation of key parts

According to the real working environment of the active balancing actuator studied in this paper, the key parts of the actuator (motor shaft, shaft key and counterweight) were simulated by ANSYS finite element analysis software. Under the working condition of 1000 r/min, the actuator rotates with the grinder and drives the counterweight at the same time. The stress concentration is analyzed. It is concluded that the structure of the active balancing actuator driven by ultrasonic motor is stable and the stress does not exceed the yield limit of the material. It provides theoretical support for the following experimental verification.

Firstly, AutoCAD software is used to obtain the size of the key parts of the actuator. Secondly, SolidWorks software is used to establish three-dimensional model. Then, the model was imported into ANSYS Workbench software to simplify the screw hole and the protruding part of the counterweight that did not affect the structural stress change, and the whole counterweight was combined into a whole part. After simplification, the material properties of the whole part of the assembly are defined. The counterweights and the motor shaft are brass alloy and the flat key is 45 steel. Meshing, determines the boundary conditions and applied load, and finally solves the stress of the model, as shown in Fig. 6.



(a) Three-dimensional model (b) Simulation model

(c) Stress (d) Stress

Fig. 6 Three-dimensional simulation of key structures

In order to determine the effect of motor shaft diameter on the structure of the key parts of the actuator, the relationship between the diameter of the motor shaft and the maximum stress of the key was simulated by ANSYS Workbench software at the speed of 1000 r/min. The simulation result is shown in Fig. 7.

From the fitting results of three-dimensional simulation, it can be seen that with the increase of shaft diameter, the maximum stress of the key is reduced accordingly, and the stress of shaft key is far less than the yield limit of the material. At the rotational speed of 1000 r/min, the whole actuator can achieve structural stability.

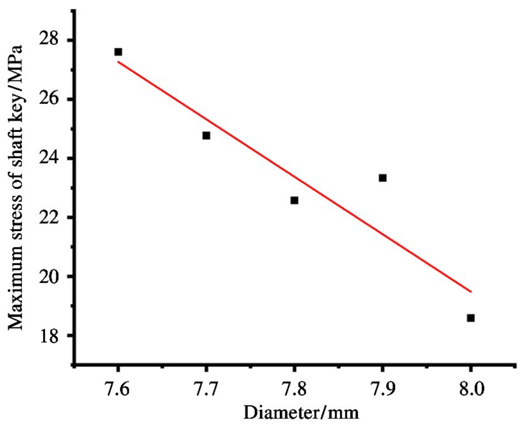


Fig. 7 Linear fitting diagram of diameter and maximum stress of shaft key

4 Experimental verification

To verify the feasibility of active actuator driven by ultrasonic motor, the actuator is processed, assembled and tested. The maximum diameter of the whole actuator is 150 mm. The balance ability of the counterweight can reach above 13 000 g · mm.

In order to verify the effectiveness of the above active balancing system, a relevant experimental platform is built for experimental verification. The experimental platform takes the grinder spindle as the object, and the balancing actuator is installed at one end of the spindle.

The acceleration sensor is used to monitor the vibration of the grinder system online, and the photoelectric sensor is used to feedback the speed information of the grinder spindle in real time. The data acquisition unit of NI is a cDAQ data acquisition device that contains two data acquisition modules and a digital output module. The two data acquisition modules are used to collect the vibration signal and speed signal measured by the grinder, and the digital output module is used to output the control instructions from the PC side, the whole experimental device is shown in Fig. 8. The vibration signal of grinding machine spindle system is analyzed online by personal computer as control unit, and the initial unbalance of grinding machine spindle system is calculated by program. The entire actuator is shown in Fig. 9, which is powered by 12V DC rechargeable battery. The control module receives the infrared signal of the remote control circuit board, and transmits the signal to the ultrasonic motor at the same time, driving the counterweight to step at a certain angle.

One side of the whole actuator close to the grinder flange is the counterweight A, and the corresponding

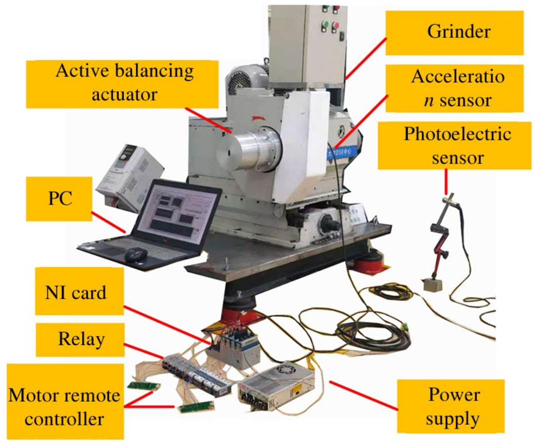


Fig. 8 Overall diagram of experimental device

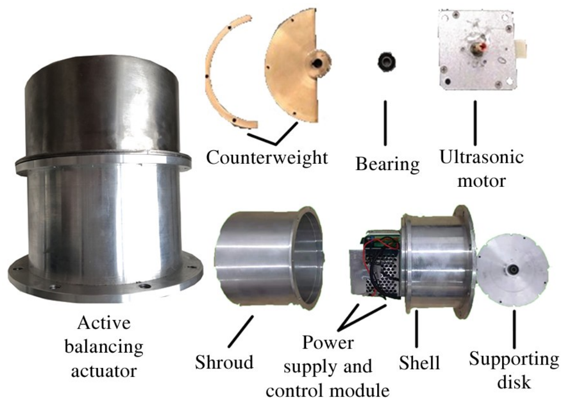
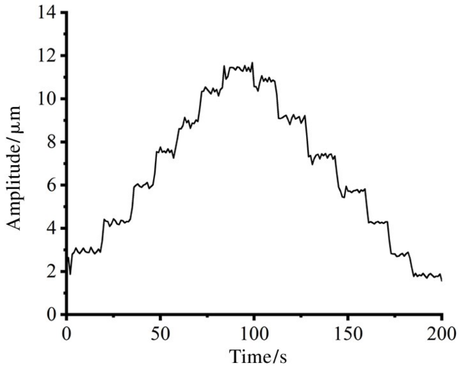


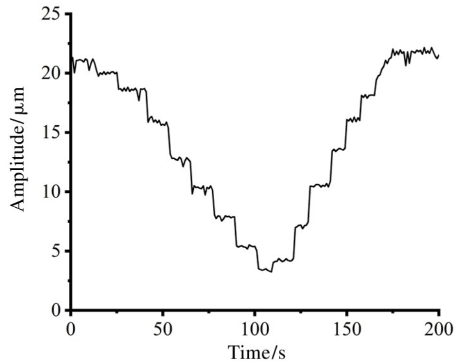
Fig. 9 Active balancing actuator diagram

other side is named as side B. The speed of the active balancing experiment is 1000 r/min to verify whether the active balancing actuator driven by ultrasonic motor is safe and stable to suppress the unbalance vibration. The B side plate is fixed and the A side plate is rotated for one week to obtain the vibration amplitude variation curve of the actuator counterweight after rotation for a whole week, as shown in Fig. 10.

It can be seen from the experimental results in the following figure that the vibration amplitude of the whole grinder test bench reaches the maximum value of 11.3 μm after the initial 2.4 μm is rotated by the counterweight for half a week. When the counterweight rotates over the position of the maximum vibration, the vibration amplitude is gradually reduced to 1.8 μm. From Fig. 10(b), it can be concluded that the vibration amplitude of the outer counterweight is larger than that of the inner plate during the whole rotation cycle, gradually decreasing from the initial 22 μm to 4 μm, and gradually increasing from the minimum value to 23 μm. The vibration amplitude difference between side A and B is mainly caused by the axial distance between two counterweight plates, which will be reduced as much as possible during the next research plan.



(a) The vibration amplitude of *A* side plate grinder



(b) The vibration amplitude of *B* side plate grinder

Fig. 10 Vibration amplitude diagram of grinder

It can be seen that after the plates on both sides of *A* and *B* are rotated for a whole week, the vibration amplitude of the grinder test bench can be effectively controlled, and the new active balancing actuator based on ultrasonic motor has no misstep phenomenon in adjusting the whole week movement of the counterweights on both sides.

5 Conclusions

A new active balancing actuator structure driven by ultrasonic motor is proposed. The working principle and basic structure of the actuator are introduced. The structure simulation of the key components of the actuator is carried out by ANSYS software. The feasibility and effectiveness of the new structure are verified by the test experiment of the grinding machine test bench. The conclusions are as follows.

(1) The principle of the new balancing method driven by ultrasonic motor is feasible. The designed structure has the advantages of no complex transmission mechanism, simple structure and fast response.

(2) The designed new balancing actuator can change its mass distribution in real time according to the control instructions under rotating conditions, and its working performance is stable. Moreover, the unbalance vibration amplitude can be effectively controlled from 11.3 μm to 1.8 μm on the grinder test bench.

In the subsequent research, it is proposed to further optimize the structure of this kind of actuator, improve the dynamic performance of the actuator, and apply it to more high-end equipment, so as to provide technical support for the engineering application of this kind of balancing actuator.

References

[1] MEI X S, ZHANG Y, DU Z. High Precision Dynamic Balance Technology of Machine Tool Spindle[M]. Beijing: Chinese Science Press, 2015

[2] PAN X, HE X T, WU H Q, et al. Optimal design of novel electromagnetic-ring active balancing actuator with radial excitation[J]. *Chinese Journal of Mechanical Engineering*, 2021, 34(1): 1-14

[3] GOYAL D, PABLA B S. The vibration monitoring methods and signal processing techniques for structural health monitoring: a review[J]. *Archives of Computational Methods in Engineering*, 2016, 23(4): 585-594

[4] QIAO X L, ZHU C S. The active unbalanced vibration compensation of the flexible switched reluctance motorized spindle[J]. *Journal of Vibration and Control*, 2014, 20(13): 1934-1945

[5] PAN X, PENG R X, HE X T, et al. Electromagnetic active balancing actuator based on the radial excitation and permanent magnet-electromagnetism combined driving method[J]. *Journal of Vibration and Shock*, 2021, 40(2): 23-28

[6] FAN H W, JING M Q, WANG R C, et al. Actuating principle of online automatic balancer with counter weight driven by magnetic force[J]. *Journal of Xi'an Jiaotong University*, 2013, 47(2): 97-102 (In Chinese)

[7] ZHAO X S, CHEN L, LI Z Q. Status research of active balancing machine for spindle of ultra-precision machine tool[J]. *Aviation Precision Manfacturing Technology*, 2014, 50(5): 6-9, 13

[8] ZHANG X N, LIU X, ZHANG W W, et al. Control strategy and tests of balancing device for liquid injection and discharge type grinding wheel[J]. *Journal of Vibration and Acoustics*, 2018, 38(15): 223-230

[9] YUN X L, MEI X S, JIANG G D, et al. Design and experimental research of a spray-type integrated online dynamic balance terminal[J]. *Journal of Vibration and Shock*, 2019, 38(10): 79-84

[10] XU X B, CHEN S, ZHANG Y N. Automatic balancing of AMB systems using plural notch filter and adptive synchronous compensation[J]. *Journal of Sound and Vibration*, 2016, 374: 29-42

[11] QIAO X L, ZHU C S. Experimental study on controlling actively wheel unbalance vibration[J]. *Journal of Vibration Engineering*, 2017, 30(1): 55-61

[12] DENG H B, GUO J C, WANG W Q, et al. Research on single-plane dynamic balance adjustment method of spindle electromagnetic slip ring balance head[J]. *Journal of Shenyang Jianzhu University (Natural Science)*, 2019, 35(2): 355-364 (In Chinese)

[13] FAN H W, SHAO S J, YANG Y Q, et al. Mechanical auto-balancing motorized spindle and its experiment[J]. *Manufacturing Technology and Machine Tool*, 2019(3): 50-54

[14] GAO J J. Artificial self-recovery and machinery self-recovery regulation system[J]. *Journal of Mechanical Engineering*, 2018, 54(8): 83-94

[15] ZHAO C S, ZHU H. Development and application of ulyrasonic motors technologies[J]. *Machine Building and Automation*, 2008, 37(3): 1-9

[16] PAN X, WU H Q, WANG Y Y, et al. Integrated Ultrasonic Motor Automatic Balancing Device[P]. CN patent: CN110768453A, 2020

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