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Characteristics of motorized spindle supported by active magnetic bearings

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Abstract A motorized spindle supported by active magnetic bearings (AMBs) is generally used for ultra-high-speed machining. Iron loss of radial AMB is very great owing to high rotation speed, and it will cause severe thermal deformation. The problem is particularly serious on the occasion of large power application, such as all electric aero-engine. In this study, a prototype motorized spindle supported by five degree-of-freedom AMBs is developed. Homopolar and heteropolar AMBs are independently adopted as radial bearings. The influences of the two types of radial AMBs on the dynamic characteristics of the motorized spindle are comparatively investigated by theoretical analysis, test modal analysis and actual operation of the system. The iron loss of the two types of radial AMBs is analyzed by finite element software and verified through run-down experiments of the system. The results show that the structures of AMB have less influence on the dynamic characteristics of the motorized spindle. However, the homopolar structure can effectively reduce the iron loss of the radial AMB and it is useful for improving the overall performance of the motorized spindle.

1. Introduction

Worldwide, ultra-high-speed machining technology, which has much high cutting and feeding speed than the conventional, is recognized as one of four major advanced manufacturing technologies. A motorized spindle combines motor shaft and machine tool principal axis without belt and gear transmission and it is the most critical component of ultra-high-speed machining equipment. Generally, the motorized spindle is supported by ball bearings.[1]

Unlike ball bearing, active magnetic bearing (AMB) does not suffer from mechanical contact and wear, has less noise, does not require any lubricant and sealing, and is characterized by long service life.[2,3] A motorized spindle with AMBs features adjustable support stiffness and damping, high rotation precision, and easy real-time monitoring. Owing to the above assets, AMB can also be applied to aero-engine.[4]

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To improve the dynamic characteristics of motorized spindle, many new control strategies for AMB have been proposed.[5–8] Furthermore, motorized spindle suffers from a problem that the large temperature rise can cause severe thermal deformation and thus reduce machining accuracy.

Miroslaw et al.,[9] utilized infrared camera images to identify major heat sources in the machine tool and they evaluated the thermal expansion of the machine by means of finite element analysis. Tamura et al.,[10] developed a motorized spindle with a self-cooling function and used rotational experiments to demonstrate that it could minimize the thermal deformation. Zhang and Li[11] used finite element analysis to simulate the temperature field, steady-state temperature distribution, transient temperature distribution and thermal error of a spindle system. Uhlmann and Hu[12] presented a 3D finite element model to predict the thermal behavior of a high-speed motor spindle. Li and Zhao[13] effectively reduced the axial thermal error at varying spindle speeds by compensating the thermal error using predicted data. Sheng et al.[14] analyzed the steady temperature field and the thermal deformation of the spindle and they proposed a solution to install a cooling sleeve in front of the spindle box, which can apparently reduce the thermal error of the spindle. Zhang et al.,[15] adopted a serial and a parallel grey neural network to predict the thermal error and they validated their method through experiments on the spindle deformation in the axial direction on a five-axis machining center. Horiuchi et al.[16] analyzed the influence of the thermal behavior of the spindle on the machining accuracy in micro-endmilling. Lu et al.[17] established a finite element model of the thermal characteristics of a motorized spindle and studied the distribution of the spindle steady-state temperature field and effect of spindle speed and bearing lubrication on the thermal deformation of the spindle. Li et al.[18] developed a prototype motorized spindle supported by five degree-of-freedom AMBs, investigated the relationship between temperature rise, grinding head posture and the controller's five reference inputs, discovered the serious effect of the temperature rise on the precision of grinding and introduced online adjustment of the grinding head posture and automatic thermal expansion compensation into the system. Wu and Hu[19] analyzed the temperature field of a magnetically levitated grinding spindle by finite element software, adopted a thermal infrared imager to measure the temperature field distribution and mentioned the importance of thermal design and structural design on the temperature distribution of the system.

A motorized spindle supported by AMBs has two internal heat sources: AMBs and the built-in motor.[20] The surface eddy current and hysteresis loss of AMBs are important factors in temperature increase. The problem is particularly serious on the occasion of large power application, such as all electric aero-engine. Therefore, it is essential to investigate approaches by which the surface eddy current and hysteresis loss of AMBs can be reduced. In this study, heteropolar and homopolar AMB are developed for motorized spindle respectively. The influences of the two types of radial AMBs on the dynamic characteristics of the motorized spindle are comparatively investigated by theoretical analysis, test modal analysis and actual operation of the system. The iron loss of the two types of radial AMBs is also analyzed by ANSOFT MAXWELL 3D software and verified through run-down experiments of the system.

2. Test device

Fig. 1 shows the mechanical structure of the motorized spindle prototype. The rotor (working speed: 60000 r/min) is supported by two radial AMBs and one axial AMB and it is driven by a built-in motor (power: 1 kW). Rotor vibrations can be detected in real-time by five pairs of differential displacement sensors.

Generally, a radial AMB has a heteropolar structure, i.e., the N and S poles are cross-arranged along the circumferential direction. When the rotor completes a revolution, the magnetic line of force reverses several times at the same position on the rotor surface. Although a lamination-type stator and rotor are generally used, the surface eddy current and hysteresis loss are still obvious and serious. The situation is different in a homopolar structure, in which each pair of magnetic poles is distributed along the axial direction and only N or S poles are located along the circumferential direction, without reversing the magnetic line of force; therefore, the surface eddy current and hysteresis loss are slight and little, respectively, and only the machining process becomes slightly more complicated.

Fig. 2 shows the structures of homopolar and heteropolar AMBs, respectively. According to the design of the structure parameter, the nominal air gap C_{r0}, bias current I_{r0} and maximum electromagnetic force F_{rmax} of the two types of radial AMBs are 0.2 mm, 2.5 A, and 20 N, respectively. For the axial AMB, the corresponding values are 0.2 mm, 2.5 A and 50 N; furthermore, the rotor length l is 218 mm, symmetry center distance of the two radial AMBs l_1 is 127 mm and two ball bearings are used as protective bearings.

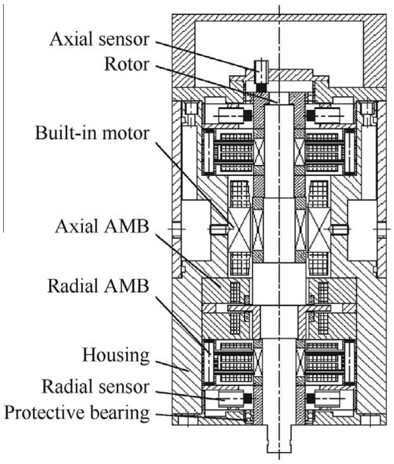
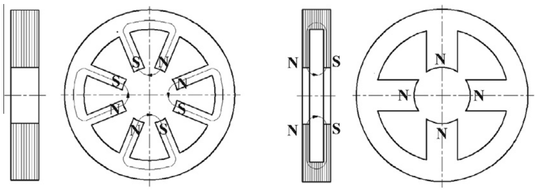


Fig. 1 Mechanical structure of motorized spindle.



(a) Heteropolar AMB (b) Homopolar AMB

Fig. 2 Schematic diagram of AMB.