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Investigation of non-uniform preload on the static and rotational performances for spindle bearing system

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ABSTRACT

In order to eliminate the deflection of spindle under external loading, a new non-uniform preload for spindle bearing system is proposed in this paper, and the effect of non-uniform preload on the static and rotational performances of the spindle system is explored both theoretically and experimentally. Seeking to reveal the role of non-uniform preload in spindle static and rotational performances under external radial loading, the equivalent transformation model is firstly built to simplify the non-uniform preload applied on the bearing. Then a simulation model is employed to analyze the variable static and rotational performances of spindle under different preload conditions. A test rig is designed to equip with spindle bearing system, inside which the measurement system is arranged to experimentally investigate how the spindle static and rotational accuracy are influenced by non-uniform preload, varying external load and rotating speeds. The results under different preload conditions show that the non-uniform preload with reasonable equivalent magnitude and direction can effectively adjust the spindle rotating center and compensate the spindle rotation error, and thus improves the rotational accuracy of the spindle system under complicated and alternating working conditions. This provides a new compensation method to the spindle deflection and rotational motion error through adjusting the non-uniformly distributed preload on the spindle bearing system.

1. Introduction

It is becoming more demanding in metal cutting for machine tools to develop toward higher speed, accuracy, productivity and intelligence. One of the most important issues among those is to meet the requirements of machining accuracy and efficiency when machine tools are working under complicated conditions. As a key component of machine tool, the stiffness and rotational accuracy of spindle bearing system directly affects the machining process as well as final quality of work pieces [1]. Given that the spindle bearing system constantly operates under alternating working conditions such as low speed during rough machining and high speed in smooth finishing, it is essential to secure the system so as to maintain high rotational accuracy, stiffness and reasonable heat transfer properties. Furthermore, in order to realize the continuous machining process for work piece, a machine center usually combines multiple machining capabilities such as milling, drilling, grinding, etc., which asks for all kinds of working modes of the spindle system to meet the different requirements of machining performance.

In general, initial preload on ball bearing is often used to obtain high stiffness and increase rotational accuracy of spindle system, and proper preload has a great impact on spindle stiffness, rotating precision, heat generation and service lifespan [2,3]. The axial preload, when applied properly on bearing, cannot only reduce the clearance between rolling elements and the inner or outer rings, but also decrease vibration as well as prevent sliding of ball bearing in ring raceway at high speed, both of which in turn lead to an increment of stiffness and rotational accuracy of bearing. On the other hand, neither too large nor too small preload is favorable since the resultant increased heat generation from large preload could shorten bearing lifespan, whereas the accuracy will be low due to inadequate stiffness if the preload is small. Therefore, it is critical to choose a reasonable preload for a good performance of spindle bearing system.

The most common methods generally applied in industrial production of machine tool are constant preload and rigid preload [4,5]. The values of preload are determined either by theoretical calculation or empirical knowledge during spindle assembling process. However, these two preload methods have a serious disadvantage that the preload values are set at constant level and could hardly be modified or readjusted once the spindle

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assembling process is finished. The inappropriateness is especially significant when the spindle system is working under alternating machining process such as heavy cutting at low speed and light external loading at high speed. It leads to low stiffness, overheating or shorten lifespan of spindle bearing system and could hardly adjust itself to varying working conditions to meet requirements for various performances. There are also other preload methods available and unfortunately, all come with obvious drawbacks. For example, the position preload may cause bearing failure as an outcome of excessive heat brought by increment of bearing preload during thermal expansion at high speed. Constant pressure preload is utilized in the spindle systems operating under heavy cutting conditions, but the low spindle stiffness owing to insufficient preload can hardly guarantee machining accuracy.

Therefore, many studies have been conducted to study the variable spindle preload method in which bearing preload can be adjusted in line with different working conditions (such as spindle speed) in real time, so as to avoid the shortcuts of overheating while still maintaining high stiffness and rotational accuracy. Several automatic adjustable preload mechanisms have been developed to modify spindle preload using different techniques and principles such as centrifugal force [6–8], electromagnet [9,10], hydraulic pressure [11–13], and piezoelectric actuators [14,15]. In these variable preload mechanisms, effects of varying preload on both static and dynamic performances of spindle system have been widely studied, aiming to find the optimum preload for better dynamic stiffness as well as lower heating generation of spindle bearing system. Lin reported that increasing bearing preload could ensure higher spindle stiffness and reduce the spindle deflection as well as its rotational error [16]. This effect has also been demonstrated on a preload switching spindle using magnetic external radial loading device by Matsubara A et.al [17,18]. Jiang studied rotational spindle stiffness with varying preload using hydraulic system with an unbalanced disk to exert radial loading on spindle nose [12]. The unbalanced disk fixed on the spindle has a few effects on dynamic properties of spindle system, and it may differ a little from the actual machining process because of the varying direction of centrifugal force produced by a rotational unbalanced disk. For turning and milling conditions, the cutting force is approximately along the constant radial direction of spindle.

The dynamic performance of spindle bearing system with varying preload has also been investigated by several researchers [19–21]. E. Ozturk particularly studied the effect of variable preload on spindle dynamic performance using the hydraulic system on a machine center, which allows an automatic and controllable preload. It has been demonstrated through tests that increasing preload could ensure a higher spindle dynamic stiffness [13]. In addition, the rotational accuracy is also among the most important performances of spindle system, which can directly affect the quality of product. Though increasing the preload can obtain higher spindle rigidity, it may not be useful for compensating or reducing the spindle deflective error because of exceeding heat generation with the increasing preload at higher speeds. Several researchers introduced adaptronic spindle system with piezoelectric actuators to compensate the spindle deflection and improve its rotational accuracy [22,23]. Sarhan proposed to explore the effect of preload on the compensation for spindle deflection and rotational motion error by using preload switching mechanism in spindle system [24]. Denkena also presented an active preload based on actuators module to compensate the radial thermal deflection caused by unevenly distributed spindle heating generation [15]. Some other researchers reported the effect of increasing bearing preload in promoting the running accuracy of high speed spindle system [25]. Kim also demonstrated that spindle rotational accuracy is highly dependent on the spindle

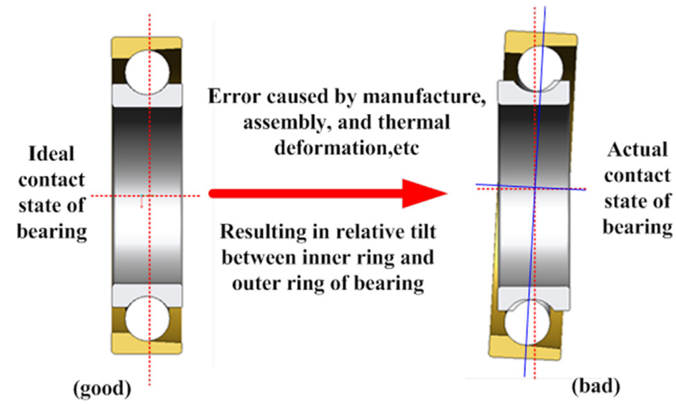

Fig. 1. Bearing tilt due to different types of error.

rotational speed and bearing preload and that increased preload from light to heavy can result in a decreased spindle run-out [26].

It is worth noting that in these advanced spindle bearing system with switching preload or controllable and modifiable preload mechanisms, preloads are applied evenly distributed on the outer ring of the bearing, and most of these corresponding studies are mainly focused on uniformly preload on spindle system. However, in actual metal cutting process, the ball bearing in spindle system often subjects to non-uniformly distributed loads due to the roughness error of spacer in manufacturing, the non-coaxial error of spindle in assembly, and unevenly thermal deformation error of bearing in spindle rotation, which not only can deteriorate the contact state in ball bearing, but also result in the relative tilting of the bearing (see as Fig. 1). Furthermore, the external radial load during cutting can also cause the deflection of spindle as well as the misalignment between the outer ring and spindle, which will lead to the rotational motion error and low accuracy of spindle bearing system. As such, applying the uniform preload on bearing is not able to improve the bad contact status in ball bearing and increase the rotational accuracy of spindle bearing system.

Therefore, it is essential to adopt the non-uniformly distributed preload on bearing to optimize the contact status of bearing and then study its effect on static performance as well as rotational accuracy of spindle system so as to compensate and reduce the spindle deflective error under external cutting load and eventually the rotational precision of spindle bearing system (see as Fig. 2).

Nowadays, little investigation has been conducted to improve the spindle performance by exerting the non-uniformly distributed preload on bearing. Wu first presented the non-uniform preload on spindle bearing system, focusing mainly on the effect of non-uniform preload on the heating and thermal characteristic of spindle bearing system [27]. Therefore, more efforts should be necessarily made on decreasing and compensating the spindle deflection as well as rotational error, especially when spindle

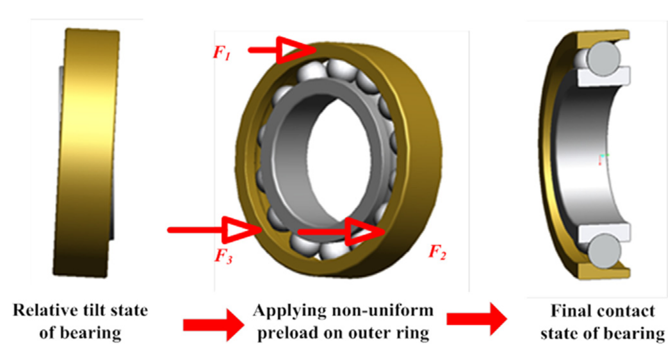

Fig. 2. Purpose of applying non-uniform preload on bearing.