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A speed-dependent variable preload system for high speed spindles

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ABSTRACT

High speed machine tools are required to operate in a wide range of spindle rotational speeds with high stiffness and high accuracy. The stiffness of the spindle is largely dependent on the axial preload of the angular contact bearings. A large preload is required at lower range of speeds to provide sufficient stiffness for vibration-free heavy cutting. However, at higher speeds, it results in rapid temperature rise and reduces the life of the bearing. For optimum performance, it is essential that the bearing preload is reduced as the rotational speed increases. In this paper, an automatic variable preload system is proposed that changes the preload on the bearings as a function of rotational speed. This system is based on the use of centrifugal forces and requires little space inside the spindle. The performance of this mechanical system is determined using finite element modeling. A prototype of the system is fabricated and its performance is investigated using a specially devised test stand for direct measurement of the preload. The effectiveness of the proposed system in reducing the preload at higher speeds is demonstrated.

1. Introduction

Nowadays, the high speed machine tools are often required to perform in a wide range of applications; from heavy cutting at low speeds and high torques to fine finishing at high speeds and low torques [1,2]. High speed spindles used in these machine tools often use angular contact bearings with initially large axial preloads. The preload on the bearing play a significant role in the performance of the spindle. The axial preload increases the stiffness and rotational accuracy of the spindle by decreasing the clearance between the raceways of the bearing and rolling elements, restraining the vibrations, as well as preventing the slip between the rolling element and the inner raceway at high speeds [3,4]. However, the preload is known to have unwanted side effects as it amplifies frictional torque and consequently increases frictional heat generation in the bearing. Therefore, this limits the maximum achievable rotational speed of the bearing and also reduces its life [2–5]. These damaging effects are aggravated at high speeds because the preload is intensified due to the centrifugal force acting on the rolling elements and thermal expansion of the components.

In order to increase production rate, it is desirable to propose machine tool systems which are capable of operating in a wide range of rotational speeds and material removal rates. At low speeds, high material removal rate is achieved by machining at higher cutting depths. Therefore, higher preload is required to increase stiffness of the system and resist deflections and vibrations. At high speeds, a smaller preload must be applied in order to reach higher speed rotation without overheating the system and shortening the life of bearings. Therefore, it may be advantageous to have a variable preload system which applies high preload at low speeds and reduces the preload as the rotational speed increases.

In some of the existing machine tools, variation of preload is achieved by employing hydraulic or pneumatic mechanisms that control the bearing preload [6,7]. For example, Zverev et al. [8], Jiang et al. [9] and Cao and Altintas [3] used hydraulic-based mechanisms for applying variable preload. Also, Song et al. [10] investigated the variable preload structure based on a pneumatic mechanism. These systems are effective in a large speed range, but are costly and require relatively large space within the spindle.

Other approaches for variable preload systems have been proposed as well. Mechanisms based on piezoelectric actuator are proposed by Tsutsui et al. [11] and Nye [12]. Chen and Chen [13] developed an active bearing load monitoring and control mechanism by using of integrated strain-gage load cells and piezoelectric actuators, so the optimal preload is identified according to the cutting conditions and the lowest bearing temperature rise. Kitamura et al. [14] introduced a mechanism that used shape memory alloys for applying variable preload.

In a recent work, Hwang and Lee [15] proposed a mechanical system that exploited centrifugal forces for achieving variable preload. This system converts the centrifugal forces to axial forces.

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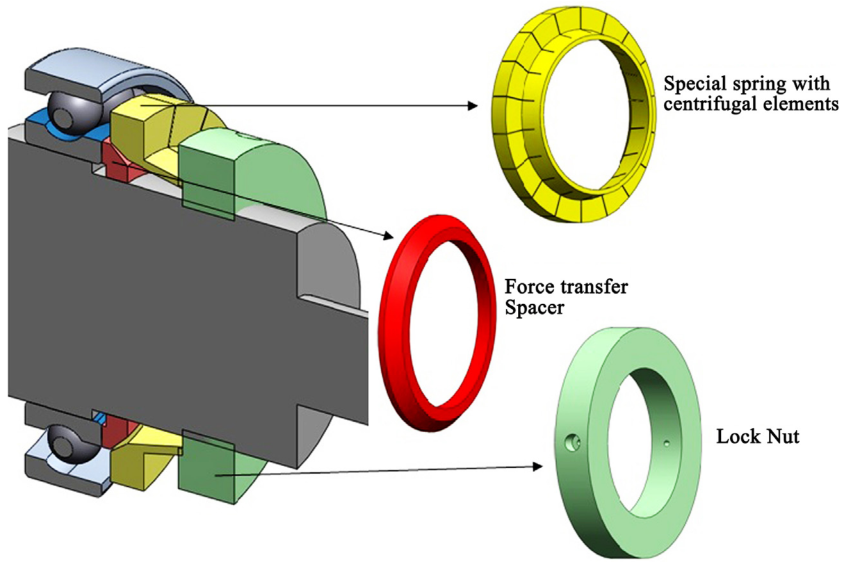

Fig. 1. The overall mechanism and components of variable preload system.

The proposed system is simple, but requires an auxiliary bearing that transmits the load on the main bearing to reduce the initial bearing preload at high speeds. In another study, they fabricated an electromagnet-based variable preload control device [16]. The force between an electromagnet and a magnet substance is used to apply preload on the rolling bearing. The load is controlled by the coil current of electromagnet. However, this device, too, needs extra equipment and space in the spindle. Choi and Lee [17] proposed another variable preload device based on changing the centrifugal forces into axial preload by using the pressure of a liquid enclosed in a chamber.

The purpose of this paper is to introduce an alternative mechanical variable preload system. Similar to reference [15], this system uses centrifugal forces to reduce the preload on the bearing as the speed increases, but does not need an auxiliary bearing. The proposed system is purely mechanical, and occupies little space inside the spindle. The main advantage of this system is its capability to induce an initial preload and directly decrease this preload at high speeds using a simple and integrated mechanism which utilizes centrifugal force instead of elaborate hydraulic and electrical feedback control systems.

The paper is organized as follows. The concept of the system is explained in Section 2. In Section 3, the details of the designed system are presented, and finite element analysis is used to predict the performance of system. Based on the FE analysis, the parameters of the system for optimum performance are determined. In Section 4, the fabrication of the system prototype is described and also an experimental test stand is designed for direct measurement of the preload. Several tests are conducted on the designed system in comparison to conventional systems (i.e. fixed position and constant pressure methods) in order to investigate the performance of the proposed mechanism.

2. Design and analysis of variable preload system

The proposed system is specially designed for preload adjustment on a spindle with back-to-back bearing arrangement. The advantage of this system is that it can be mounted inside the spindle in a relatively small space. It applies an axial preload on the inner ring of one of the bearings. Due to nature of the back-to-back bearing arrangement, the preload of both bearings will be regulated simultaneously. The preload exerted by this system is a function of rotational speed of the spindle as well as the initial axial preload induced in bearings during the assembly process. It utilizes centrifugal force to decrease preload of the bearings when the spindle speed is increased.

2.1. Design requirements

The main requirements on the automatic variable preload system are the following three characteristics: (1) enough elasticity in order to ensure reversible operation of the system, (2) appropriate mass distribution in order to generate the required amount of centrifugal force, and (3) a simple mechanism for converting the radial centrifugal force to axial preload so that by raising the centrifugal force, axial preload is decreased.

2.2. Detailed design

The overall mechanism of variable preload system is shown in Fig. 1. It consists of a specially designed ring which acts as a spring (hereinafter called spring) equipped with centrifugal mass elements, a spacer ring used for transmitting the force, and a locknut. The components of the variable preload system are assembled on the spindle and rotate at spindle speed.

The spring is made of a ring with radial slits that divide it into equally-spaced sections. Each of these sections behaves like a cantilever beam, and thus provides considerable elastic behavior allowing the piece to act as an axial spring. The end of the spring is so designed that acts like a mass element generating the centrifugal force which is used for reducing preload. On the other hand, the root of the cantilever sections is relatively thinner, and thus provides the required spring action. The spacer is a ring in direct contact with the spring.

The initial amount of preload is determined by the level of the torque applied for tightening of the locknut; its maximum value is limited by the difference between the lengths of the inner and the outer spacers mounted between the two bearings ($\left|d_o - d_i\right|$ in Fig. 2). When the nut is tightened, it causes the spring to open up on the spacer. The spring and spacer contact on an inclined surface. Therefore, only the axial component of the spring force is transferred through the spacer to the inner ring of the bearing.

The principle of reducing axial preload can be explained as follows: by tightening and locking the nut, the spring is loaded and