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REVIEW PAPER

Research Development of Preload Technology on Angular Contact Ball Bearing of High Speed Spindle: A Review

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Abstract
Preload of angular contact ball bearing (ACBB) is extremely important to high speed spindle, which has a great influence on the spindle's dynamic and thermal characteristics, etc. In this paper, the preload source of ACBB; the main preload principles, methods and their advantages and disadvantages; research progress and development trend of preload device are discussed. On the basis, common criteria for computing and choosing optimal preload; influence of preload on dynamic and thermal properties of bearing and spindle system are discussed as well. The purposes of this paper are to clarify the research idea of preload, and provide a reference for accurately calculating the bearing stiffness under sophisticated conditions, precisely controlling dynamic parameters of high speed spindle, designing preload device with excellent dynamic performance, etc.

Keywords High speed spindle · Angular contact ball bearing · Preload · Research development

1 Introduction

Modern machine tool (MT) with high-speed, high-precision and high-efficiency are develop trends in recent years, the manufacturing accuracy of aviation and semiconductor industry rise from micron to nano level, which demands the MT possesses a more excellent performance. As a core component, the static and dynamic characteristics of high-speed spindle (HSS) directly relate to machining accuracy and cutting stability. In order to adapt to large machining range, modern spindle must holds high stiffness and rotation accuracy, which means the HSS needs to offer high stiffness at low speeds and low stiffness at high speeds. Various factors can influence the stiffness of HSS, such as material, bearing stiffness, bearing span, shaft length, etc. Bearing stiffness provided by appreciate preload is not only one of the most important factors for the whole HSS system, but also deeply relate to the vibration and cutting stability of MT [1]. In manufacturing and assembly stage, bearing preload should be adjusted to achieve the best performance for HSS [2]. Under this premise, proper preload is the guarantee of excellent dynamic performance of spindle. For above reasons, the influence of preload on bearing dynamic properties and HSS characteristics should not be ignored.

At present, there are mainly 3 bearing types for HSS: magnetic bearing, hydrostatic bearing and rolling bearing. However, the costs issue of magnetic bearing and power-speed limits of hydrostatic bearing are huge obstacles, hence the angular contact ball bearing (ACBB) with low friction property and high radial/axial load-carry capacity is widely used in grinding, milling and high-speed lathe MT, etc. [3].

The method of choosing and computing preload is always a key technology for designing HSS system. Therefore, in this paper, the preload sources of ACBB, the main principles of preload, preload methods with advantages and disadvantages, research progress and development trends of preload devices are reviewed. On the bases, common criterions for calculation approaches of optimal preload, preload influence on dynamic and thermal properties of bearing and spindle systems are discussed as well. The purposes of this paper are to clarify the research ideas of preload, provide references for: (1) accurately calculating the bearing dynamic stiffness, (2) precisely controlling dynamic parameters of HSS, (3) designing preload device with excellent dynamic property, (4) accurately assembling the HSS. If not specifically mentioned, bearings referred herein are ACBBs.

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This paper is organized as follows: Sect. 1 is an overview on the importance of preload. In Sect. 2, basic knowledges about bearing preload generation, bearing layouts and preload methods are illustrated. In Sect. 3, static and dynamic preloads are introduced, then the generation procedure and simple calculation approaches of the two types are described. In Sect. 4, criterions for preload computing based on single or multiple sensitive factors are discussed in detail. In Sect. 5, prime methods for static and dynamic preloads measurement are demonstrated. In Sect. 6, a variety of devices on eliminating dynamic preload are presented. In Sect. 7, preload influence on bearing and spindle dynamic properties are discussed respectively, also the influence on cutting stability is explored in short. Finally, conclusions are obtained in Sect. 8.

2 Common Bearing Assembly and Preload Methods of HSS

Depending on bearing type and structure, bearing preload which generate from relative deformation between rolling elements and inner/outer rings can be divided into radial force and axial force. Bearing preload can be adjusted by changing its clearance to positive or negative, for example, hub bearings need positive clearance to ensure stable wheel operation, while spindle bearings of MT require negative clearance to ensure rotary accuracy.

2.1 Common Form of Spindle Bearing Combination

Single row ACBB can only withstand axial loads in one direction, in order to load and reduce spindle displacement in MT, usually more than 2 pairs of ball bearings of the same type are used in combination. Combined bearings owe various forms and flexible combinations, common types of configuration include back to back (DB), face to face (DF), and tandem (DT) [4], as shown in Fig. 1.

Under DB combination, the cantilever end of spindle possesses a high stiffness, for the load center is outside the bearing centerline, hence the acting point of force gains a large span. The bearing clearance increases when shaft is elongated under heat effect, which protects the bearing from stuck and destroy. The DF combination is a simple structure with load center locates inside the centerline and easy to assembly–disassembly, however, the bearing clearance will decrease and bearing will easily get stuck if the shaft is heated and extended, so special attention should be paid to the adjustment of bearing clearance. For the DT type, the load center locates at the same side of the bearing centerline, such combination is suitable for large axial load and multi-bearing situation. Thereinto, the DB and DF types can sustain two-way axial load, but the acting point of DB is farther than DF, hence DB is usually used to withstand torques. However, DT can only withstand one-direction axial load, but 2 pairs of DT bearing can evenly divide the axial load, which is commonly used in large unidirectional load situation. To strictly control the runout of shaft and the displacement caused by external load, DB-DF configurations are generally adopted together. All these bearing combinations mentioned above need to be preloaded before use. Li [5] studied the influence of bearing layouts on the thermal-dynamic characteristics of HSS comprehensively based on thermo-mechanical coupling model, laid a foundation for follow-up researches.

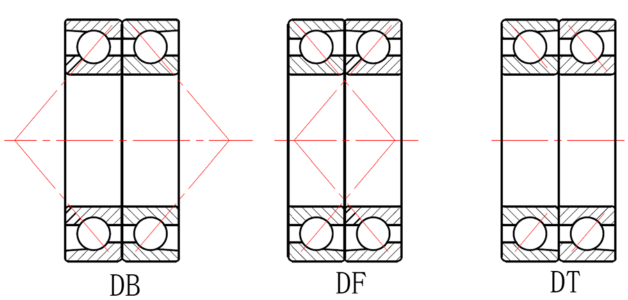

Fig. 1 Combination of ACBB

2.2 Common Layouts of Spindle Bearing

Due to the relative position of components, the built-in motor locates between the front and rear bearings of the high-speed motorized spindle. This layout is usually supported by four ACBBs at least, two more bearings at each end are mostly assembled in DT. Due to the difference of bearing size, rotation speed and groove curvature radius coefficient, the axial preloads acting on the two bearings are quite different [6]. As mentioned in Sect. 2.1, thermal expansion of bearings will significantly increase axial force and then cause bearing failure under DF combination, however, this effect can be alleviated under DB installation [7].

2.3 Common Preload Method of Spindle

According to preload principles, the existing preload technologies can be divided into 3 categories:

1. Constant preload methods: include constant position preload method, constant pressure preload method.
2. Variable preload methods: include variable position preload method, variable pressure preload method.
3. Non-uniform preload method.

Constant position preload (rigid preload) and constant pressure preload are mainstream preload methods at present. Generally, some components such as spacer, shim, lock nut are used to achieve the rigid preload condition by adjusting the relative distance between inner and outer ring. Constant pressure preload is achieved by compressing soft springs with unignorable stiffness on the outer ring of the bearing, hydraulic/pneumatic cylinders are also used to produce constant pressure preload, this method is widely accepted in HSS because it can maintain preload constant during operation. Variable preload is usually applied by a hard spring with unignorable stiffness [8]. Position preloaded bearing is sensitive to temperature variation between shaft and housing, especially in small bearing spacing condition. For floating support, preloads among bearing group will rise rapidly if the floating bearing fails to float in axial direction, which will completely eliminate the internal bearing clearance and produce radial stress, such result will be even worse for bearings with 15° contact angle. For 20° and 25° ACBBs, the sensitivity of bearing to temperature difference will decrease if a constant pressure preload bearing group with larger space is used [9]. For HSS using ACBB, the front bearing group is usually designed to sustain 2/3 of the axial force and the rear group carries 1/3 [10]. Figure 2 is a schematic diagram for illustrating the position preload and constant pressure preload methods.

Recent years, in order to vary bearing preload with cutting conditions, two individual spindles each with low-speed high- torque or high-speed high-power are installed on one MT at the same time, which is treated as an international solution, two spindles automatically switch due to processing needs. Although this method can achieve preload adjustment, it will lead to complicated machine structures and reduce production efficiency. Some researchers proposed an idea of preload control [11–13], for example, the preload control system developed by Keio University in Japan measured bearing in working state with stress sensor, and control the preload by piezoelectric actuator. According to control strategy, variable preload devices can be divided into: ① passive control device; ② active control device. The detailed preload method will be discussed in the fifth section.

For the complexity of bearing production, assembly and working environment, bearing load is not uniformly distributed along the radial direction of the ring, but the preloads that applied by previous methods to bearing rings are all uniformly distributed, which limit the full performance of bearing and are not conducive to the precise control in preload. Li [14] proposed a non-uniform preload method, they proved the proper non-uniform preload can reduce the total torques on bearing rings and reduce heat generation. Figure 3 is the 3D description of the uniform and non-uniform preload methods, the arrows with different colors and lengths represent for different preload value.

3 Source of Preload

In general, during high speed operation, the preload of ACBB come from 4 parts: (1) initial preload; (2) centrifugal force acting on the inner ring; (3) centrifugal force acting on the ball; (4) thermal induced preload.

The latter two forces which can be treated as dynamic preloads rise rapidly with the increases of speed. When designing a constant pressure preload device, bearing number and spindle length are all required to be as less as possible in order to reduce the bearing span, for the span is extremely sensitive to the temperature difference between the shaft and shell. The shaft expands in both axial and radial directions at the same time when the spindle temperature rising, thus the expansion of inner bore diameter of the shaft can increase bearing preload while the expansion of bearing span can reduce the preload. Therefore, the thermal induced preload can be compensated by selecting an appropriate inner bore/span ratio at design stage for keeping the preload constant. Due to the influence of thermal induced preload and centrifugal induced preload, a sliding sleeve is also designed for supporting the bearing to compensate the thermal displacement of the HSS, but the method is rather superficial [15].

3.1 Source of Initial Preload and Centrifugal Induced Preload

Initial preload is the basic force to ensure normal bearing operation, which is generated from preload device acting on

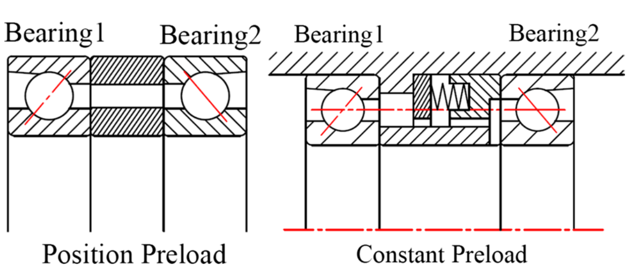

Fig. 2 Preload method for ACBB

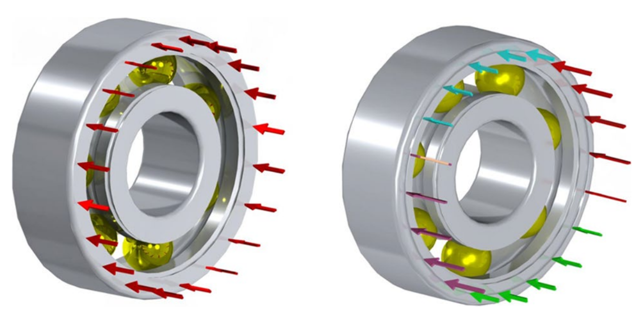

Fig. 3 3D description of uniform and non-uniform methods

the inner/outer ring at static condition, the value is usually set manually. At high rotation speeds, centrifugal induced preload (CIP) of bearing is generated from centrifugal movement of balls and centrifugal expansions of rotating parts. The calculation methods of centrifugal forces of balls and centrifugal expansions of inner rings are discussed in the references of 16 and 1, respectively.

3.2 Source and Calculation Process of Thermal Induced Preload

Thermal induced preload (TIP) is generated by the following steps: (1) frictional heat generation; (2) heat transfer; (3) thermal expansion; (4) TIP due to contact force rises. Frictional heat generation is determined by external and internal factors, such as cutting speed, lubrication condition, preload, external load, ball sliding, etc. TIP is rather sensitive to initial preload because large initial preload can cause rapid growth of the TIP. Thermal analysis of rolling bearings can be divided into 2 categories: (1) thermal growth prediction modeling; (2) failure study under large heat generation, which is often caused by bearing thermal expansion.

Theoretically, thermal deformation of bearing assembly is equivalent to the axial displacement of the outer ring, where TIP can be obtained by axial stiffness. The TIP reaches maximum when the expansions of the inner ring and ball reaching maximum. With the increases of speed, the uncertain heat transfer among inner ring, ball and lubricant increase significantly, therefore, it is difficult to calculate and predict the TIP by conventional methods [16]. Due to the interaction between TIP and temperature rise, the thermal–mechanical coupling model is a necessary basis for analyzing this problem, accurate simulations of frictional heat generation and temperature are the bases and premises for studying dynamic preload. The general generation process of TIP and the thermal–mechanical coupling model are shown in Fig. 4 [17], it clearly shows the impact factors and relationships among each step.

In dealing with the TIP, Burton [18] first studied the thermal stability of ACBB, derived the thermal-displacement static equation of bearing assembly, but the equation can't deal with dynamic preload problem. Carmichael [19] and Davies [20] analyzed the lubrication and cooling effects on the TIP of ACBB, found the TIP closely related to friction force and cooling status, in steady state, the TIP was about 6–7 times larger than non-cooling condition. Sud [21] investigated the effect of spindle speed on induced preload, established a first order differential equation of transient TIP, however, the model couldn't predict the transient preload characteristics as Carmichael and Davies found. Pruvot [22] established a thermal dynamic model and assumed the variation in contact force was only caused by the ball expansion, but some key factors like thermal expansion of inner and

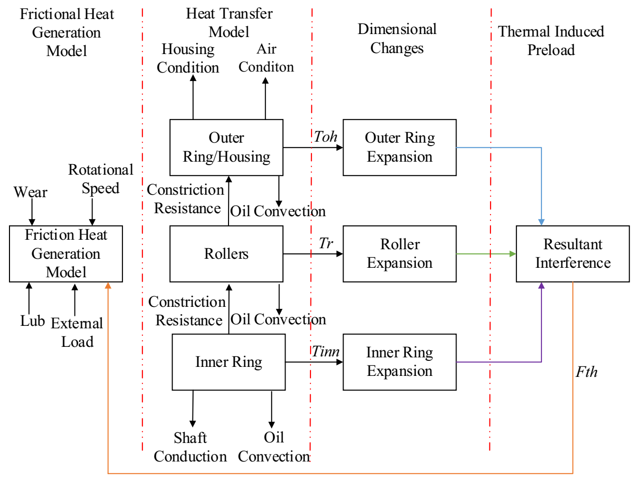

Fig. 4 Generation process of TIP [17]

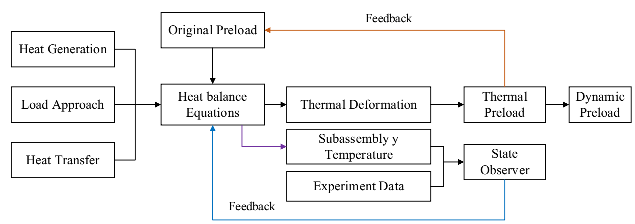

Fig. 5 Calculation process of TIP [16]

outer ring, heat transfer effect were neglected. Jiang [23] studied the cooling effect on TIP, proved the inner ring cooling has a better effect on suppressing the TIP than outer ring cooling. The state space model deduced by Stein [24] included the expansions of spindle housing and the inner/outer rings of bearing, could well compatible with the TIP and the initial preload and be used as the on-line monitoring model, however, the heat generated by centrifugal force and CIP were not considered. State space model proposed by Tu [25, 26] has greatly promoted the theoretical study of dynamic preload, the parameters of temperature on the shell and spindle speed were regarded as the feedbacks, which could well monitor the bearing dynamic preload and predicted the transient TIP. This method is often used for state observer design and is the most widely used model. Takabi [27] summarized the thermal induced damages in bearings, emphasized the existed researches mainly focused on sliding bearings instead of rolling bearings, which was due to the complex structures and kinematic motions. The general calculation process of TIP with feedback is shown in Fig. 5 [16], where the heat balance equations are core parts for obtaining an accurate result. Two deep difficulties in predicting TIP are the thermal resistance calculation and nonlinear heat generation process. Various computation methods are applied to solve these problems, such as disturbance attenuation method, thermal quadrupoles method, first order partial differential equation, etc.

4 Preload Calculation, Selection Method and Preload Criterion

4.1 Preload Calculation

In practice, it is necessary to select appropriate preload according to actual working conditions. Generally, there are 2 ways for selecting: (1) Empirical method, which is mainly estimated by technicians based on their working experience, is unreliable and inaccuracy; (2) Theoretical calculation method, because numerous impact factors exist, only the most sensitive parameters are considered for analysis and calculation. Furthermore, theoretical analysis can be divided into 3 kinds: ① fatigue life criterion; ② ball skidding criterion; ③ heat generation (temperature rise) criterion. The purpose of theoretical analysis is to obtain the most optimal preload under relevant working conditions.

Coupling methods based on multi-factor disciplines like thermodynamics are mostly used in building preload models. These methods include bearing and bearing-rotor modeling technologies, which have already been clearly demonstrated in the Refs. [28–30], won't be described in this paper.

4.1.1 Empirical Based Method

Based on preload level, this method aims to select a suitable preload considering the application range and working condition. For example, NSK divides the preload into 4 levels: micro, light, medium and heavy [31], SKF divides the preload into 3 types: light, medium and heavy, and provide the methods for computing the spacer thickness for changing the preload [32]. Bearings of HSS on grinding machines or machine centers require light or micro preload, spindles with high stiffness such as lathe spindle need medium preload. Combined ACBBs with contact angles of 15 deg and 30 deg are widely employed in MT spindles, moreover, the average preload and axial clearance have already been made into specific tables [31].

4.1.2 Fatigue Life Based Criterion

Several scholars studied the relationship between bearing life and preload, and optimized preload from the perspective of bearing fatigue life. Harris [33] indicated that proper preload can extend bearing life. Hagiu [34] showed there definitely existed a preload range that ensured the bearing life to be optimum. Hernot [35] tested the deformation of a rotor-bearing system in terms of preload, analyzed the preload effect on nonlinear stiffness and life of ACBB. Cai [36] provided the corresponding relationship between bearing preload and bearing temperature rise, regarded the bearing temperature rise as a control target, then obtained the bearing preload in high speed and in low speed range in terms of fatigue life. Hwang [37] put forward an optimization method of bearing preload, which regarded bearing life, stiffness and thermal growth as calculation bases and applied gyroscopic sliding as a criterion, the optimized preload and correlation curve between preload and bearing life were achieved after multiply weight coefficient by the individual maximum/minimum preload and summed up these results together. Zhang [38] indicated the optimum preload could be obtained by fatigue life estimation as long as the external load and rotation speed were provided. The problem about adopting fatigue life as criterion finally attributed to the study of the contact stresses between roller and inner/outer rings which simultaneously affected by centrifugal force. As shown in Fig. 6 [39], when rotation speed reaches 10,000 r/min, contact stress of inner ring (Fig. 6a) is 958.2 N/mm while the outer ring (Fig. 6b) shows 884.2 N/mm under the centrifugal influence.

4.1.3 Skidding Based Criterion

Increasing axial force is an effective means to prevent ball skidding, however, excessive axial force will result in immense contact stress that eventually decreases bearing life, thus it is necessary to determine the minimum axial force. In a rotating condition, the Hertz contact area between inner ring and ball will decrease under the effect of

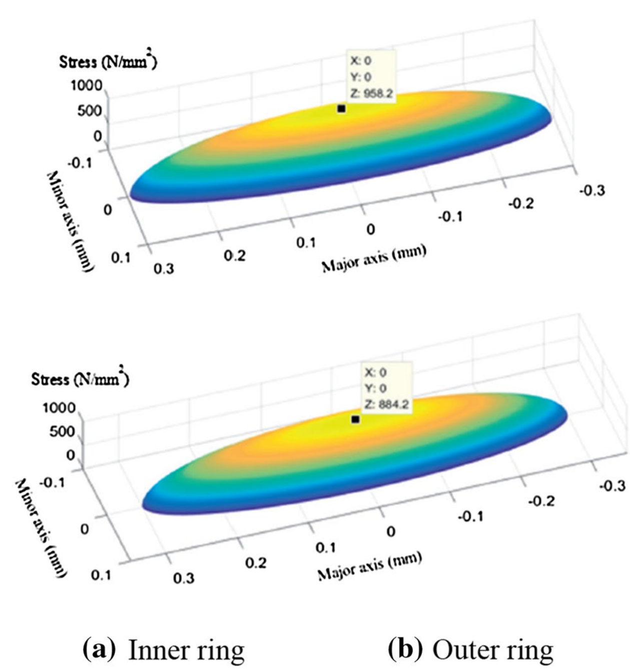

Fig. 6 Contact stress distribution on inner and outer ring [39]. **a** Inner ring and **b** outer ring

centrifugal force if the rotation speed increase continuously, which will lead to the ball skidding, when the speed rises to a certain extent, the ball will lose contact with the inner ring. In this situation, the friction and temperature increase sharply. The analysis procedure under roller skidding criterion is shown in Fig. 7 [40], compare with the fatigue life based criterion, the key problems of this method are also the load distribution and contact stress growth. Therefore, for a given preload, there must exit a corresponding critical speed area where the centrifugal contact area between the bearing inner ring and ball is zero. Yuan [41] established an elastohydrodynamic traction model of high-speed ball bearing which comprehensively considered the effects of radial/axial loads, centrifugal force and gyro torque, then obtained the maximum friction factor and minimum axial force for preventing ball skidding based on anti-skidding criterion. Xu [40] studied the relationship between optimal preload and rotation speed by regarding ball sliding as the boundary condition, obtained a reasonable result that the bearing only produced a slight temperature rise at 10,000 r/min, however, the bearing performance under other temperatures were neglected. The bearing sliding criterion can be written as [40]:

$$Q_i \sin \alpha_i \big/ P_3 \leq 10$$

where Q_i is ball load of inner raceway; α_i is inner contact angle; P_3 is centrifugal force.

4.1.4 Temperature Rise/Thermal Growth Based Criterion

It is necessary to consider the temperature of bearing group and its relative dimension when determining the bearing preload, lower shell/outer ring temperature does not always represent lower TIP. Jia [42] calculated and explained the preload amount of two preload methods based on static condition, where the preload was divided into 3 categories: light, medium and heavy, then he demonstrated the actual preload selection should refer to experience and temperature rise. Kim [43] analyzed the relationship between assembly parameters and thermal–mechanical characteristics of bearing inner ring-shaft and outer ring-shell components. Liu [44] computed the preload under two working conditions of low speed heavy load and high speed light load respectively based on the criterions of stiffness and temperature rise.

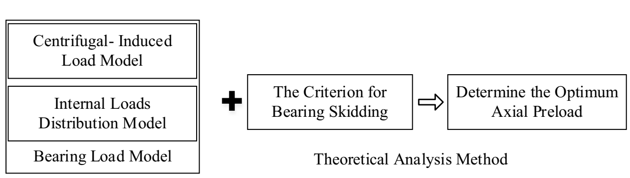

Fig. 7 Preload analysis route based on ball skidding criterion [40]

4.1.5 Multi-parameter Based Criterion

The single-parameter criterion mentioned above are slightly insufficient for the preload estimation accuracy, several researchers in pursuit of multi-parameter based criteria. Li [45] determined the minimum working preload of bearing under non-gyro spinning assumption at high rotating status, deduced the relationship between dynamic preload and initial preload considering the influence of high speed and high temperature working conditions. Xu [46] employed the power spectrum density method to study the frequency response of the spindle under different preload and rotation speed, predicted the connection between frequency characteristics and the preload. Xu [47] indicated that motor current value, bearing vibration, temperature rise and preload varied with rotation speed when the constant pressure preload was applied.

4.2 Minimum Preload

Hirano [48] first studied the minimum preload. Jones proposed a formula for calculating the minimum preload based on gyro torque prevention. Xu [47] believed the correlation between maximum preload and rotation speed could be determined if the bearing service life and reliability factors have been obtained. Jiang [49] analyzed the minimum preload of ACBB under two kinds of preload manners, discovered the diversities existed in speed-minimum preload reaction relating to steel ball and ceramic ball: the minimum preload increased with rotation speed in steel ball (which was exactly dissimilar as the general recognition that high speed bearing should be lightly preloaded) while didn't increase with rotation speed in ceramic ball. To prevent ball from sliding, the minimum axial load required for ceramic ball should be much smaller than steel ball. There is a specific critical preload corresponding to each rotation speed, and the radial flexibility doesn't not vary with rotation speed under this preload, this flexible saturation phenomenon has been found in almost every HSS. Therefore, the preload should not exceed the critical value when selecting spindle preload. Zverv [50] discovered the value of this threshold was about the median, or 10–15% below the median value as recommended in bearing catalog.

4.3 Optimal Preload Determination

4.3.1 Affecting Factors on Preload

Because of the complicated usage environment, bearing characteristics are suffer from numerous influence factors,

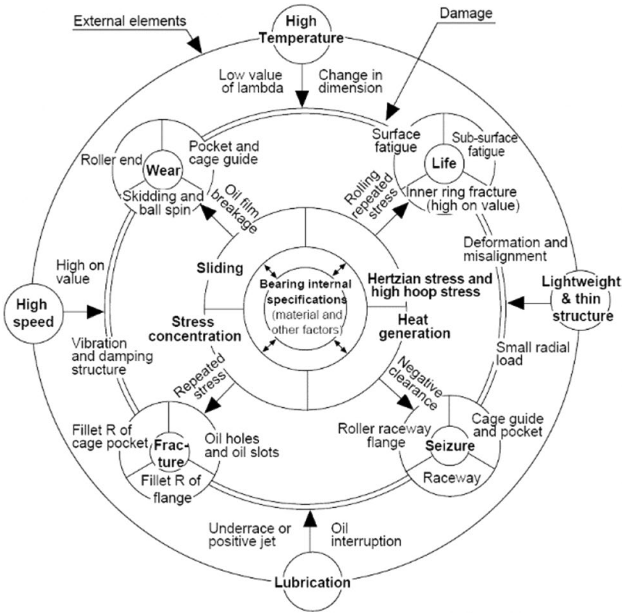

Fig. 8 Bearing influence factors [51]

these impact factors are summarized and illustrated as cycle by Lacey [51] shown in Fig. 8, where the speed and temperature are two significant factors while sliding and heat generation are two important criterions. Meanwhile, any individual factor is not act separately, however, they are coupled and affect each other. Hence it is a challenging task for accurately computing the preload [37]. Hwang [28] attributed the spindle bearing preload technologies to 2 parts: (1) Optimal preload determination; (2) Research on reliable bearing preload device.

4.3.2 Optimal Preload

In order to achieve the best performance of running bearings, it is necessary to determine the optimal preload. Preloads achieved by the criterions mentioned above are the minimum preloads instead of the optimal preloads. Optimal preload is tough to calculate either because the shaft of HSS is affected by much factors [52]. It is often believed that large initial preload can produce high temperature, this conclusion is true for ordinary spindle, but it is not fully applicable for HSS. For HSS, the optimal preload increases with the increases of rotation speed. Such speed-based variation of preload can be explained by ball skidding, that is: HSS requires large preload to ensure sufficient Hertz contact area to prevent ball skidding [53]. All bearing manuals provide basic criterions for preload selection manners under full contact assumption of balls and channels, but these criterions are invalid at high speeds. Zverv [50] proposed 2 calculation criterions: (1) the classical criterion, which means all rollers are fully contact with raceway under ideal running state of spindle; (2) rollers don't slide on raceway under gyro torque effect at high rotation speeds. In combination with the above criterions, Zverv [50] achieved the optimal preload range regarded of ring-roller contact rate and bearing life.

Hagiu [34, 55] researched the determination problem of bearing preload under specific high-speed conditions, analyzed the influence of axial preload on the bearing service life and dynamic stability, and studied the optimal preload of a pair of ACBBs. Chen [53] developed an active monitoring-control device to select the optimal bearing preload by judging cutting state and bearing minimum temperature. The ideas proposed by Jiang [56] was: applied low speed large preload to fulfilled the life requirement and adopted high speed small preload to control heat generation. The optimal preloads corresponding to various speed ranges were obtained eventually, but the TIP of shaft was neglected. The results showed both temperature rise and dynamic stiffness of the spindle were improved when the optimal preload was applied. Zhang [57] studied the preload-vibration, preload-temperature rise and preload-service life respectively, selected a suitable constant preload for 170SD30-SY ceramic motorized spindle. Qiu [58] designed a dynamic test rig to determine the minimum bearing preload at different speed. By combining the bearing fatigue life model and the internal stress distribution model, Xu [47] optimized the preload based on multi-parameter criteria with respect to bearing life reliability condition, analyzed the rotation influence on internal stress distribution and contact angle variation, obtained the optimal preload by adjusting the reliability of the fatigue life model. Dong [54] proposed a complete calculation method to obtain the optimal preload, with impact factors such as bearing stiffness, temperature rise, fatigue life and ball sliding considered. Figure 9 [54] is the relationship between the optimal preload when the three factors acting simultaneously, where the bearing skidding is the

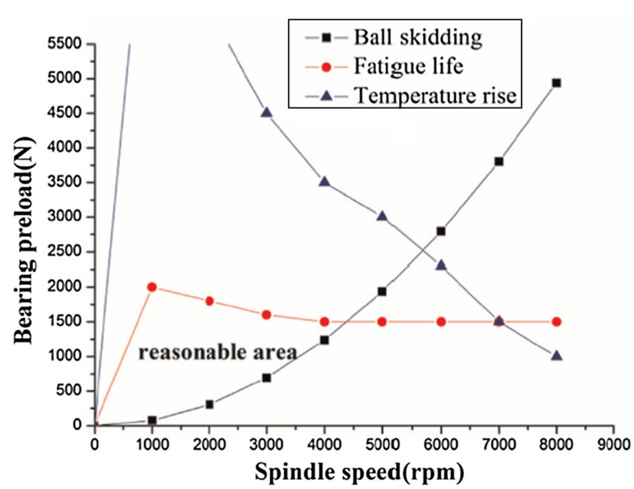

Fig. 9 Optimal preload of bearing under combined factors [54]

minimum boundary condition, the relationship between the initial preload and the fatigue life is the maximum boundary condition for preload computation.

It is seen that large amounts of researches have focused on the subject of bearing preload. However, for the optimal bearing preload closely relate to various impact factors, plenty of necessary experiments are still needed to be implemented to determine the optimum preload on the basis of theoretical analysis [59].

5 Preload Measurement

Preload measurement is a prerequisite for achieving optimal preload control.

5.1 Off-Line Measurement Method for Initial Preload

1. *Dimensional control method* It is one of the most commonly used methods to manage the preload by controlling the outer diameter tolerance of spindle and the inner diameter tolerance of bearing. Once the bearing is mounted on the spindle, the preload is impossible to alter, only the removal of the bearing can achieve such purpose.
2. *Starting torque method* The main scope of this technique includes low-speed spindle and high-stiffness spindle, which is widely adopted by spindle factories and users, this method is not suitable for HSS with light preload because of the difficulty in detecting torque difference in a precise preloading controlled spindle.
3. *Axial static stiffness method* In this method, the preload amplitude is obtained by analyzing the bearing stiffness characteristics, and the stiffness is acquired by the load-deformation ratio of spindle, this method is usually combined with the size control approach and is also one of the most commonly used methods in spindle factories.
4. *Strain gauge method* Strain gauge is stuck on the outer ring of assembled bearing for preload measuring, and the preload is regarded as internal force of the system. Due to the complexity of the system, this method is mainly used in academic research.

   Except the strain gauge method, all the other methods mentioned here are indirect manners, the performances of precision and repeatability unable satisfy the HSS well. Lots of error sources exist in these classical ways, such as dimensional tolerance, error caused by rolling balls, zero drift, etc. [60]. The operation steps of the above methods are complicated and the test results are greatly influenced by subjective factors, which needs a huge effort to guarantee the accuracy and efficiency, hence, it is not suitable to adopt this approach in special occasions with high precision and limited operating space.
5. *Natural frequency method* Natural frequency method is widely applied in spindle assembly workshop. It is applied to monitor the preload after bearing assembly and compare the frequency characteristics of spindle under the same conditions. Figure 10 shows the operation procedure of natural frequency method. Commonly, vibration is excited by hammer method and the corresponding signal is picked by vibration sensor, then the natural frequency is converted into spindle stiffness. The correlation between spindle preload and natural frequency is studied by Mannan [61], and the relationship was reflected by the corresponding monitoring test under the same support span [62]. This technique can be realized theoretically when the preload is in nonlinear deformation range, but it is difficult to quantify the preload by this method because of myriad impact factors.

Other measuring approaches and instruments have been developed and designed as well: Walford [63] proposed a method for measuring the stiffness of rolling bearing systems under oscillating conditions and designed a corresponding measuring device. Tsuneyoshi [60] introduced a preload measuring manner based on multi-factors, including size control, starting torque, axial static stiffness, natural frequency and strain gauge. Hu [64] developed a comprehensive parameter tester for precision ACBB, which can exert preload well in assembly, however, this tester was design for navigation system, not for HSS.

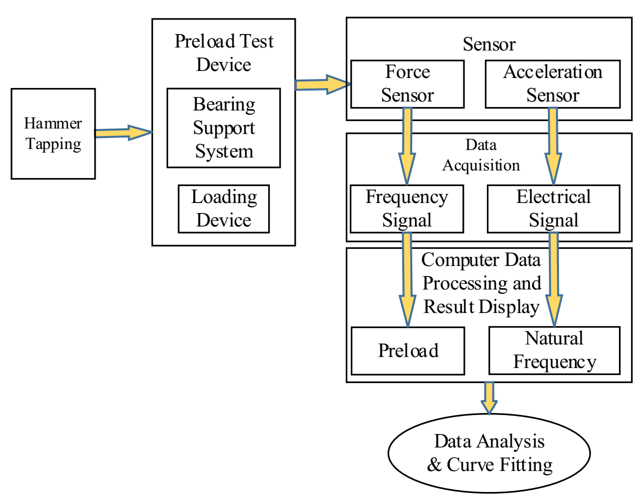

Fig. 10 Operation procedure of natural frequency method

5.2 On Line Monitoring Method of Preload

3 ways are capable of protect HSS from thermal induced failure: (1) keep the preload constant; (2) monitor the bearing temperature rise online and shut down the HSS urgently at emergency, this method is widely accepted; (3) forecast and predictively adjust the preload in accordance with the running state of HSS, which consists of 2 steps: ① pre-programming according to the operating state of HSS to avoid rapid and large alteration in heat generation; ② online correction, which is appropriate for a variety of bearing types, can extend bearing life and eliminate non-warning downtime [65].

Tu [66] carried out a research on online preload monitoring, built a test rig based on state space model, and used the signals of bearing outer ring and spindle housing as feedbacks, the model can precisely predict TIP occurring on spindle and bearing and compensate errors caused by interference signals such as test noise and ball skidding. Spiewak [65] developed a complete testing method for obtaining spindle stiffness by an exciter and a vibration sensor mounted on the spindle component to estimate the transient preload. Li [67] employed resistance strain gauges to detect the bearing preload indirectly. Turek [68] compared the advantages and disadvantages of the existing variable preload devices, then designed a test bench to measure the deviation of ACBB preload of HSS in running status for active preload adjustment.

5.3 Centrifugal Induced Preload Measurement

Measure the HSS in real time by conventional method when it rotates at high speeds is extremely tough, not to mention the situation that bearings are installed in spindle. Some scholars use contact method to measure the bearing, for example, Chang [69] and Spiwak [65] obtained the preload variation and rotor expansion by signal processing in terms of the spindle housing, which was relatively complicated. Cao [70] indirectly verified the predicted results by the natural frequency method described in 4.1. While a majority of studies applied non-contact methods for measurement, due to volume, price and stability impact, the rotor position and expansion amount were usually measured by capacitive, inductive or eddy current sensors, however, the measurement results of these transducers rely heavily on environmental parameters, material and temperature, and the calibration was time-consuming. In order to avoid such testing defects, Gunthera [71] accurately measured the centrifugal expansion and vortex trajectory of a high-speed rotor based on multi-sensor system constituted by laser doppler distance sensors. Czarske [72] measured the centrifugal expansion of a high-speed rotor by array interferometers, but these two tests were only for specific rotor test benches, not for bearings.

5.4 Thermal Induced Preload Measurement

Due to the obstruct effect of seal structure and spinning effect of bearing, mount sensors into rotating bearing is nearly impossible, hence the internal temperature of spindle, initial preload and TIP are all hardly to measure directly, most studies use indirect approaches to measure the induced strain of shaft and shell. In order to improve spindle assembly, Carmichael [19] used strain bridge method to measure the TIP of bearing during operation. Pruvot [22] indirectly measured the internal temperature of bearing based on rotation speed, bearing outer ring temperature and spindle housing temperature for monitoring the alteration of the TIP. Takabi [73] indicated the parameters such as rotation speed, lubricating oil viscosity, and thermal resistance had significant effects on TIP, and illustrated the time-varying curve of the TIP, as shown in Fig. 11 [73], where the solid rising curve means a large portion of frictional heat generated inside the bearing with the ball's temperature was much higher than other components, hence the TIP grew rapidly in the first 400 s, with the heat dissipation, temperature difference among balls, rings and housing became small and the curve decreased until reached zero, which indicated the thermal expansion of housing were lager than bearing balls and rings. Obviously, the TIP can drop down to non-zero value if the boundary condition changed, as the dotted curves showed.

Due to the complexity and variability of ACBB, the experimental test methods for online monitoring of dynamic preload are strictly limited in practical applications. In order to achieve dynamic monitoring, Yan [16] deduced a thermo-mechanical coupling model of ACBB considering temperature and preload compensations, obtained thermal

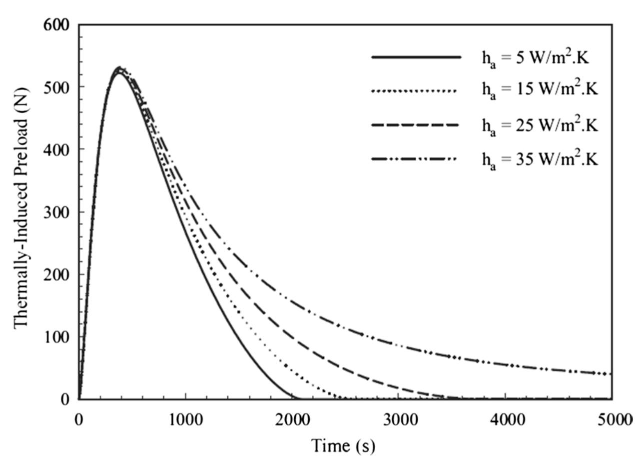

Fig. 11 General variation law of TIP [73] ($n = 2000\,\mathrm{r/min}$)

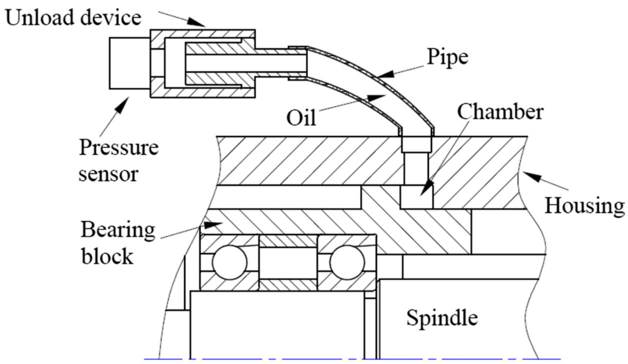

Fig. 12 Unload device of TIP for ACBB [54]

deformation and TIP data based on heat balance equation, the nonlinearity and uncertainty of heat transfer were studied by state space method, then the real-time temperature rise, thermal deformation and dynamic preload were acquired. Dong [54] designed an unloading device to prevent the effect of TIP. As shown in Fig. 12, the tube which is formed by the spindle housing and the bearing seat is connected to the cavity, both the tube and cavity are filled with oil, the oil pressure that can transmit force to the bearing outer ring through the seat in the pipe is monitored by pressure sensor, the oil pressure is adjusted through the fine screw in the pipe. When the TIP is applied to the bearing outer ring, the total preload can be reduced by increasing the inner space of the tube.

6 Preload Device and Its Research Status

For the purpose of eliminating the tremendous influence of TIP, scholars have done lots of theoretical and experimental studies on preload control. On the one hand, a variety of new design methods are explored, such as using low expansion coefficient materials, floating bearings at one end of the spindle to absorb axial thermal expansion, reducing the thickness of bearing outer ring to rapidly absorb thermal expansion acting on inner ring and ball, using DB combination to balance the radial and axial thermal expansion, etc. [26]. On the other hand, various adjustable preload techniques and instruments are developed.

The adjustable preload methods can be roughly divided into 2 categories due to control principle: ① nonreal-time control, which can be achieved by changing bearing structure or applying compensation principle, such as hydraulic preload [74]. ② Real-time control, preload is measured by means of deformable element on bearing seat in working status and controlled by a certain component, as described in Refs. [75, 76]. At present, constant pressure preload and variable pressure preload methods based on nonreal-time control have been applied. Companies such as GMN, IBAG, DIXI, MAZAK, and YASDA have successfully applied one of these technologies in some high-performance motorized spindles [13]. With respect to preload mode, the adjustable manner can be divided into active and passive method. Active preload devices are regarded as linear actuators that are capable of controlling bearing preload accurately, including hydraulic, pneumatic, electromagnetic, centrifugal and piezoelectric actuators, etc. [77]. However, such implements (especially centrifugal preload devices) adjust the preload in accordance with bearing temperature or rotation speed, fail to guarantee the spindle-bearing system work in the permanent optimal state [78]. Meanwhile, drawbacks remain exist in the instruments mentioned above, for instance, equipment with excessive price restrain the widespread use, weak stability including lubrication deterioration, repeated start-stop status of HSS, bearing wear, large cutting force, poor cooling restrain the usage in various operational conditions of MT, Therefore, it is necessary to develop low cost technology with on-line monitoring and compensation for adverse thermal effects, which is a growing urgency with the increase of spindle speed.

6.1 Typical Preload Devices

6.1.1 Hydraulic/Pneumatic Preload Device

Bossmanns [79] adopted a hydraulic preload device in thermo-mechanical coupling experiment of spindle. 23 circumferential springs were compressed by hydraulic pressure to provide axial preload for front bearing. In term of stiffness and temperature, Teng [80] selected appropriate preload and adopted hydraulic mechanism. Jiang [56, 81], Zverev [82], Cao [83] et al., used springs and hydraulic cylinders to apply preload on bearings. Figure 13 [12] is a hydraulic preload structure, obviously, hydraulic fluid is filled in the

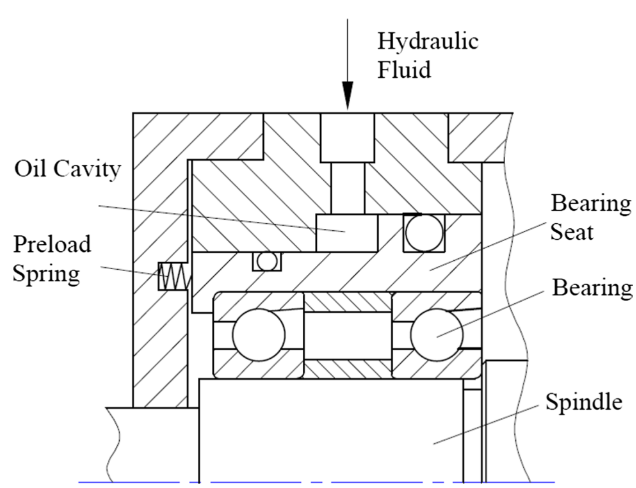

Fig. 13 Hydraulic preload structure [12]

oil cavity to force the movable bearing seat generate a horizontal displacement, which finally acts on the outer ring of the left bearing. Controllable hydraulic preload mechanism is the most popular variable preload method at present. The instrument not only has a long travel, but also can produce a large force. But there are 2 drawbacks [84]: ① the relationship between bearing speed and preload is not accurate enough, the displacement resolution is usually greater than 10 μm with low response speed; ② high cost. Pneumatic components are commonly used as force-applying structures as well, as reported by Song [85] and Chen [86].

6.1.2 Centrifugal Preload Device

Although centrifugal force that generated by rotating components play great negative effects on the dynamic characteristics of HSS, it still possesses positive effects if using some conversion structures. Such devices can be divided into 2 categories in terms of the conversion medium: ① mechanical type; ② flexible medium based on centrifugal principle.

Centrifugal preload mode is able to produce a wide range of force since centrifugal force is a quadratic function of rotation speed. Hwang [87] adopted auxiliary bearing to transfer axial force generated by centrifugal structure to the main bearing, as shown in Fig. 14a [87]. Dong [88] developed an eccentric block preload instrument with eccentric mass provided by nut and axial preload variation depending on nuts distribution. Kim [89] improved the structure and increased the applicable speed from 6000 to 10,000 r/min. The device designed by Razban [90] can automatically convert centrifugal force into axial force and transmit it directly to the inner ring through the wedge-to-wedge fit without auxiliary bearings, as shown in Fig. 14b [90]. Compared with other methods, the device can significantly reduce the axial preload at high speeds when considering thermal expansion. The relation between preload and rotation speed indicates that the centrifugal variable preload instrument is more suitable for finishing stage with small cutting force and small requirement on support stiffness instead of high speed and high stiffness machining.

In addition to the above structures, scholars have developed deformable rubber [91] and liquid preload device [92] based on material properties and centrifugal principle, as shown in Fig. 15a [91] and b [92] respectively. The main structures are similar despite of the conversion mediums, preloads are generated from the deformed mediums under centrifugal effects, where the liquid preload device owns excellent fluidity and shape adaptability. However, the liquid leakage and seal under dynamic contact need more attention.

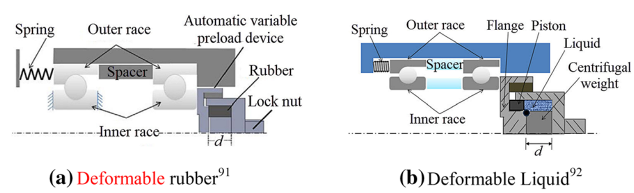

Fig. 15 Deformable rubber and liquid preload devices

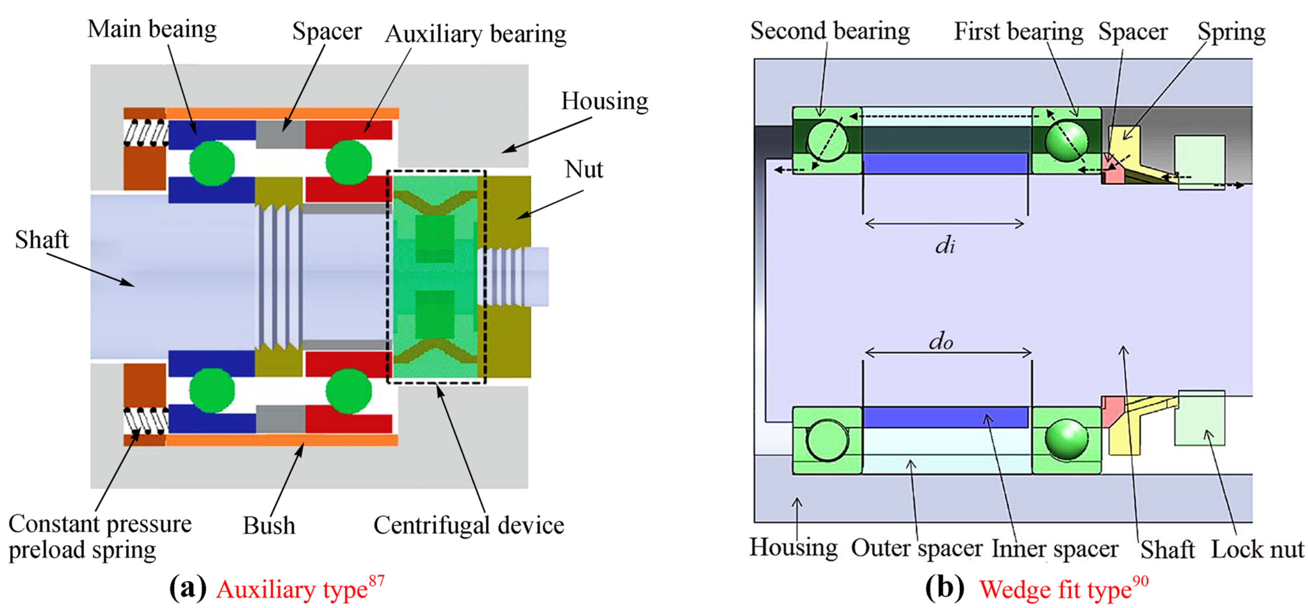

Fig. 14 Centrifugal preload devices

6.1.3 Electromagnetic Actuator Preload Device

Electromagnetic actuator preload mechanism is designed based on the principle of electromagnetic. Nye [93] carried out relevant studies in early stage. Hwang [84] developed an electromagnetic preload device that control the preload by adjusting the coil current, the preload owing to the displacement of the movable part under the effect of traction force that generated by the electromagnet. As shown in Fig. 16 [84], the device is composed of electromagnets, moving parts, fixed parts, etc. Preload acting on outer ring is produced by compressed spacer under the effect of magnetized axial moving parts when electromagnetic suction created by conductive coil. Electromagnetic suction which constrained by structure volume is controlled by the input current and proportional to the current size. Following disadvantages still exist on electromagnetic equipment besides their simple structure: ① both the input current and air gap are quadratic in relation to the output force, hence precise load control is definitely a tough task under the nonlinear effect of the output; ② large volume is require to generate sufficient preload. The electromagnetic preload device with higher efficiency improved by Hwang [94] was successfully applied to a certain type of motorized spindle, as shown in Fig. 17. The spindle stiffness was increased by 14% comparing with constant pressure preload, and the hysteresis problem was improved by current control strategy.

Compare with the hydraulic instrument, the electromagnetic preload mechanism possesses high displacement resolution and fast response speed, but serious heat generation and excessive volume can cause severe negative effects on the high acceleration/deceleration of the MT. It is necessary to optimize the volume-output force ratio in order to improve the device to be more suitable for large-scale preloading, other problems such as magnetization and degaussing of components should be noticed and solved, where a special designed cooling equipment might be helpful.

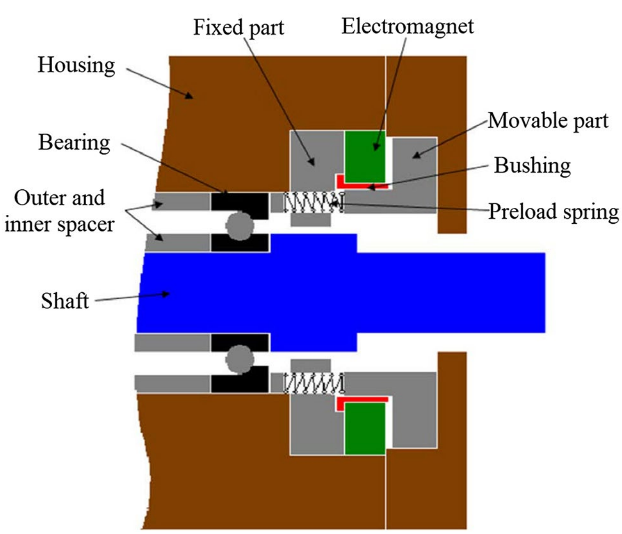

Fig. 16 Electromagnetic preload device [84]

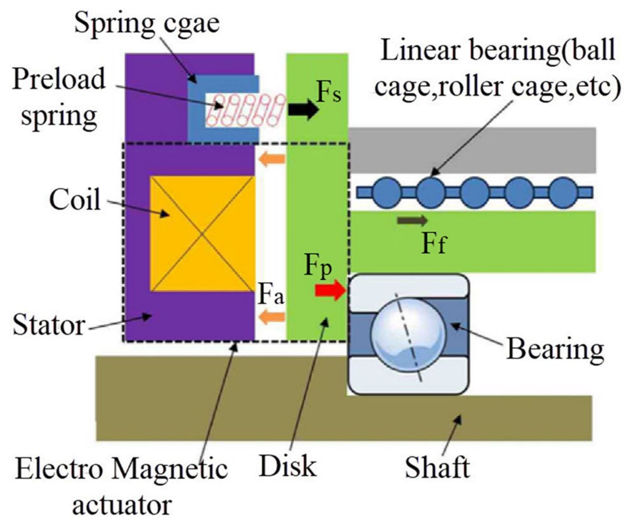

Fig. 17 Improved electromagnetic preload device [94]

6.1.4 Shape Memory Alloy Preload Device

Shape memory alloys (SMA) are commonly used to control the critical speed of rotor-bearing system, the concept first proposed by Nagaya [95] and Viderman [96], critical speed can be avoided by changing bearing stiffness of the rotor during the speed up/down stages. Lees [97] altered the bearing preload and stiffness by varying the shape of SMA installed on the elastic ring with heating. As shown in Fig. 18 [97]. However, the device adopted a radial preloading mode, and the radial directions were not homogeneous.

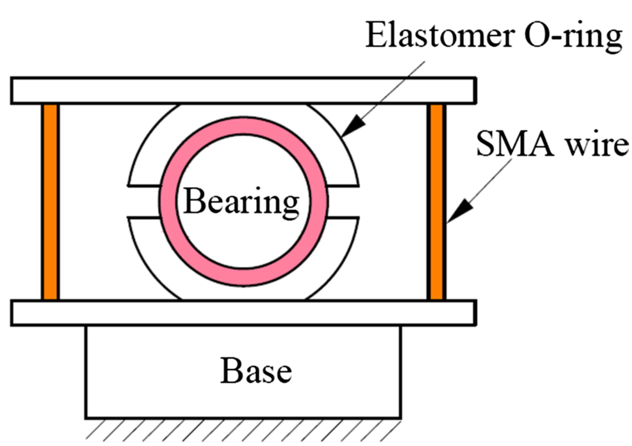

Fig. 18 Shape memory alloy preload device [97]

Tom [98] presented a SMA-based preload adjuster prototype, but the structure was not described in detail.

6.1.5 Piezoelectric Ceramic Preload Device

Piezoelectric ceramics (PZT) is a functional ceramic material with mutual conversion property of mechanical energy and electrical energy. Moreover, it is widely applied in micro-control field with advantages of high output power, fast response, small volume, noiseless, heatless, etc. In spindle preload technique, the PZT is placed inside the main shaft and directly contact with the bearing outer ring.

Tsutsui [100] and Chen [101] developed an active preload device based on piezoelectric actuators, but the device was open-loop control and failed to obtain force values directly. To overcome this inherent disadvantage, Chen [99] installed a strain gauge in the piezoelectric actuator for improving the output linearity and the device sensitivity. As shown in Fig. 19 [99], 3 actuators are uniformly distributed in the bearing outer ring with 120 deg interval each, which results in an uniform preload applied on the axial direction. This preload structure was used in a motorized spindle developed by Taiwan National Centre College [99]. Whereas none of the studies mentioned above referred the design and control approaches of preload actuators.

Ma [102] developed a controllable preload mechanism based on laminated PZT. Li [67] selected PZT as the force-applying component and analyzed the effect of preload on spindle vibration and bearing temperature rise after verified the method feasibility. Wang [13] developed an adjustable preload mechanism based on PZT and flexible hinge structure, as shown in Fig. 20 [13]. The piezoelectric actuator is used as driving source while the flexible mechanism is fixed around the bearing sleeve through a flexible hinge. Input displacement and driving force are generated in accordance with the expand/contract of PZT, which is controlled by voltage adjustment depending on the preload variation requirement of spindle system. Under the action of flexible hinge, the input displacement and driving force are transferred to the connecting rod through the input rod and flexible hinge and finally to the output rod, at last, force is yielded on the out ring for bearing preloading.

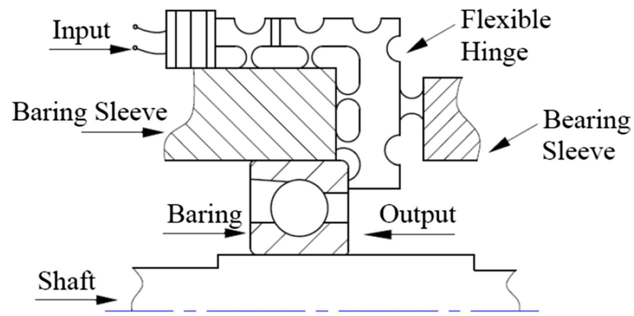

Fig. 20 PZT and flexure hinge based preload structure [13]

The piezoelectric preload mechanism developed by Hu [78] can achieve the mutual conversion of variable pressure preload and variable position preload, as shown in Fig. 21 [78]. 3 piezoelectric actuators and 3 displacement transducers locate at the ends of rear bearings and are evenly distributed around the sleeve. Initial and dynamic preload are obtained by the adjustable fine thread bolts and piezoelectric actuators respectively. Variable pressure preload is achieved when the front and rear bearing are preloaded by dynamic force and system reaches balance in axial direction. Variable position preload can be realized by big clearance due to high preload when high voltage is applied on the piezoelectric actuator, and vice versa. Uniform preload will be received if the forces generated by the 3 piezoelectric actuators are equal, otherwise, it will be non-uniform preload.

Although piezoelectric actuator holds excellent fine-tuning performance, response speed and high rigidity, it has plenty of disadvantages in addition, such as nonlinear lag, DC drift, fragility and small displacement. For the difficulty in producing large force when driving directly, high voltage with thousand volts is required, which is challenging to achieve and much costly in manufacturing.

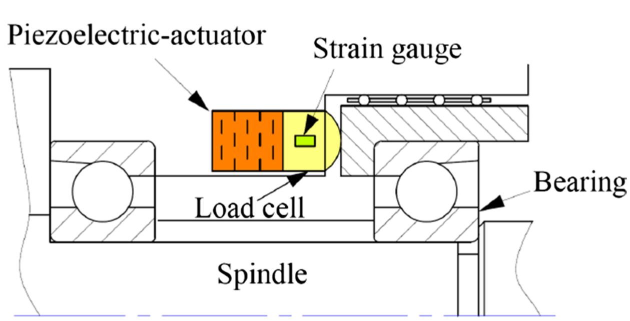

Fig. 19 Piezoelectric preload actuator with strain gauge integrated [99]

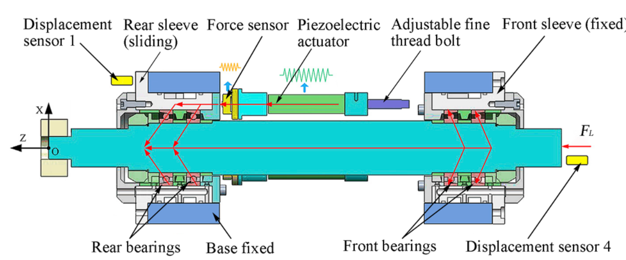

Fig. 21 Variable pressure/position preload mechanism [78]

6.1.6 Other Bearing Preload Devices

Chen [103] reported an adjustable preload device based on liquid plastic with the properties of wide adjustment rate, high accuracy, sensitive feedback, simple construction and strong practicability, while it was arduous to adjust automatically. Guo [59] designed a controllable preload mechanism based on stepper motor. Hagiu [104] developed a feedback mechanism for maintain preload balance of spindle on the basis of analyzing the interaction of stress distribution, thermal expansion and assembly tolerance in bearing. Yang [105] designed a variable preload device with double-layer sleeve based on two unique thermal expansion materials through simulation verification, as shown in Fig. 22 [105].

In summary, the performance parameters of the preload actuator include: action area, repeatability, response time, energy efficiency, drive power, size, weight, etc. Therefore, the performances mentioned above should be considered comprehensively when designing a preload device.

6.2 Researches on Preload Control Strategy

Accurate control is indispensable to the preload adjustment, on the contrary, there are few reports about the control strategy and corresponding effects on the spindle performances.

The control of variable preload is mostly based on preload-speed curve (or other parameters such as air gap length) obtained from experiments, which can be fitted by regression analysis. Electromagnetic preload, with the difficulties lay in how to accurate and smooth control, are lack of discussion in most papers. The piezoelectric actuator can produce a hysteresis error when the voltage fluctuates, which is greatly affected by load, acceleration and speed. How to decrease the hysteresis error and keep the multiple actuators consistent is the difficulty of control. The hydraulic dynamic preload control technology adopted by Gilman Precision [106] in high precision spindle can change preload according to the characteristics of the material being processed. Based on PID closed-loop control, Tu [26] adjusted the temperature rise of housing by controlling the cooling of the spindle for the bearing TIP control. Guo [59] determined the optimal preload of a precision grinding spindle with a real-time control system on the basis of the PID control principle and algorithm. For spindle-bearing system with hybrid preload mechanism, Hu [78] adopted PI controller based closed-loop control method, carried out the step response control and trajectory tracking control on the preload and the related displacement. Due to the high-speed effect, how to keep the bearing's actual preload constant and adjust the corresponding output of the piezoelectric actuator in real time are also difficulties.

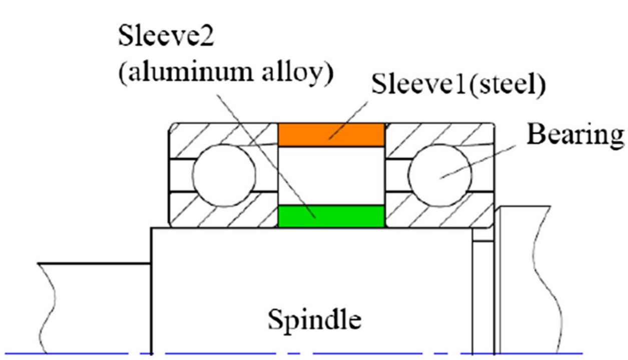

Fig. 22 Bearing preload structure with double sleeve [105]

7 Impact of Preload

7.1 Preload Influence on Bearing

7.1.1 Preload Influence on High Speed Effect of Bearing

ACBB generates large centrifugal force and gyro moment at high speeds. The centrifugal force reduces the contact stress between the ball and the inner ring, causing the ball to slide along the raceway while the gyro moment forces the ball rotates around its axis. The ball will slide along the gyroscopic pivot when friction moment provided by the contact area between the inner and outer rings is less than the gyro moment, hence gyro pivot sliding should be avoided at high speeds [15]. The preload has little effect on the centrifugal force, in other words, the centrifugal force under large preload is slightly smaller than under small preload. On the contrary, with speed increases the rising speed of the gyro moment of ball under small preload is higher than under large preload. Change rate of contact angle which varies with rotation speed also declines when preload growing [107].

7.1.2 Influence of Preload Methods on Bearing Stiffness

Stiffness prediction is one of the crucial steps when designing a HSS, unfortunately, few papers have focused on the bearing stiffness characteristics under preload modes. For predicting the dynamic response of spindle system, it is indispensable to establish an accurate bearing stiffness matrix [29]. The classical bearing stiffness equations mainly include radial and axial stiffness in static status, while the bearing dynamic stiffness of HSS changes with load in rotation condition. Li [108] established an axial dynamic stiffness model of a constant pressure preloaded spindle, derived the relations between the axial dynamic stiffness and axial load. With the increase of preload, the inner contact angle of bearing decreases, while the outer contact angle increases, furthermore, centrifugal force, gyro torque and spin-roll ratio of ball decrease, contact deformation/stress/load and bearing stiffness of ball and inner/outer rings increase. The dynamic characteristic parameters of bearings under constant pressure preload are greatly affected by preload variation, but non-sensitive with the fixed position preload [109]. Yi [110] studied the dynamic changes of contact parameters of constant pressure preloaded bearings: when the ball was subjected to gyro torque and centrifugal force, the outer ring moved axially, thermal expansion generated by friction heat could aggravate the heat rise at high rotation speeds, meanwhile, the relative motion of the inner and outer rings under above effects would conversely reduce the thermal expansion of the ball. Zhang [2] researched the inner ring deformation under centrifugal force and assembly stress and deduced the corresponding bearing stiffness model. He indicated the 2 factors had disparate influence on the dynamic characteristics of pressure/position preload bearings. When rotation speed or radial external load increased, the bearing stiffness under constant pressure decrease rapidly, which wouldn't occur on position preloaded bearing. It is seen that position preload has high stability for the maintenance of preload and is suitable for low speed heavy cutting, while constant pressure preload is more suitable for high speed cutting due to temperature rise reason. However, regarding of the unstable characteristics, it is particularly critical to select an accurate preload for constant preloaded bearing at high speeds. Figure 23 [29] shows the effects of preload methods and rotation speed on the radial stiffness of ACBB, the variable preload is generated by a stiff spring. It clearly demonstrates the differences between constant and position preload, and shows the advantages on stiffness maintains of variable preload comparing with the other two manners as the speed increases.

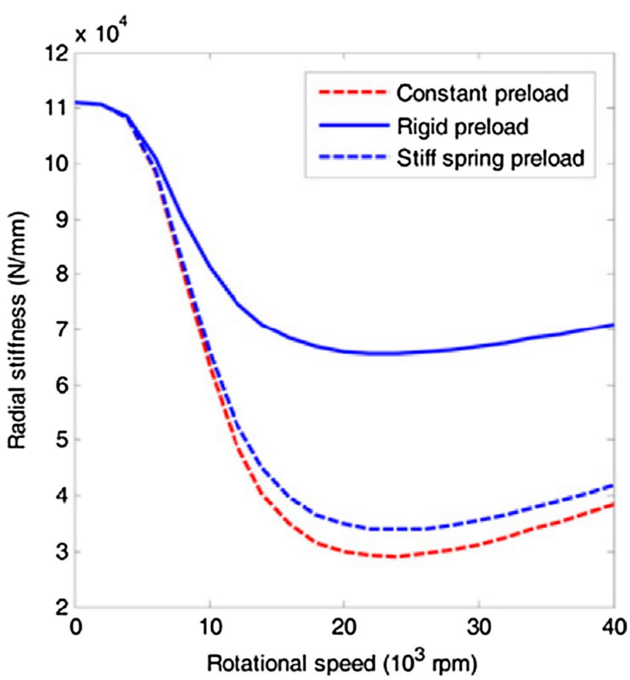

Fig. 23 Effects of preload methods and rotation speed on the stiffness of ACBB [29]

7.1.3 Preload Effect on Bearing Critical Speed and Fatigue Life

Chen [6] analyzed the preload distribution of ACBB and discovered the preload difference initially decreased and then increased when the rotation speed increased within a certain range. The size deviation has the greatest influence on the axial preload distribution, followed by rotation speed and groove curvature radius coefficient. Yi [110] indicated the bearing stress state can be improved by optimizing the channel coefficient. Zhang [111] established a dynamic bearing wear model based on starved lubrication condition, analyzed the interaction of wear status exist on inner/outer ring and preload under various preload manners, in addition the comprehensive influence on bearing life. Lacey [112] experimentally obtained the nonlinear relationship between preload and speed, indicated the preload was only stable at a certain critical speed. Huang [113] studied the preload effect on the critical speed of HSS, found the spindle's critical speed would drop if the preload declined. Rabreau [114] tested and uncovered the bearing preload and stiffness were the most sensitive parameters. Zhang [38] discussed the effects of external load, rotation speed and preload on raceway-ball contact state of ACBB and the bearing fatigue life under above influences by static and quasi-dynamic models, as shown in Fig. 24 [38]. It can be seen the bearing fatigue life first rises and then decreases with the increase of preload in both static (not given in this paper) and dynamic models, and the clearance corresponding to the preload is positive at the optimum fatigue life. The number of loaded balls is rare

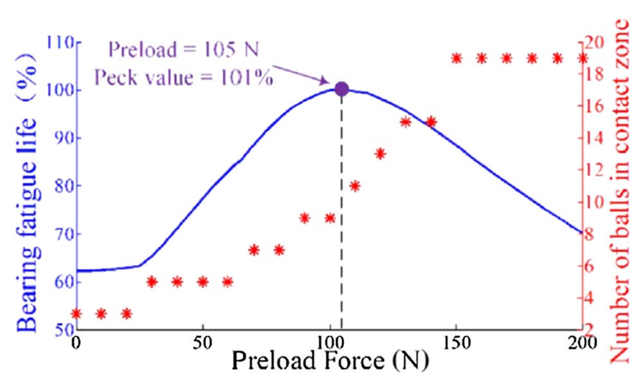

Fig. 24 Variation curve of fatigue life with preload (quasi-dynamic model) [38]

when the preload is small, but each ball bears an excessive load, which will accelerate the fatigue failure of the bearing.

At present, there are still rare comprehensive studies about the bearing stiffness change rule and influence factors under different preload mechanisms. The dynamic contact parameters in contact area of ACBB under dynamic conditions have not been discovered in existing literatures, such as contact points and contact forces [115].

7.2 Preload Influence on Spindle

7.2.1 Comprehensive Influence of Uniform Preload on Spindle Dynamic Characteristics

Bearings can't work independently, hence the research of bearings should be placed in actual circumstance, which is the basis for the dynamic characteristic analysis and thermo-mechanical coupling analysis of HSS [3, 116]. Currently, innumerable researches focus on the relationship between bearing preload and spindle performance. For example, Oouchi [3] experimentally studied the correlation between spacer clearance and dynamic characteristics of spindle. Cao [83] emphasized that preload could raise the 4th frequency instead of the 1st order frequency, even if the two frequencies closely relate to the spindle stability. The spindle vibration profiles are similar under unequal preload, the natural frequency of HSS, the dynamic compliance of tool point and the damping rate decline with the preload reduction [11]. The critical speed increase along with the preload rise, while the spindle vibration has a contrary trend, however the decrease tends to slowly when the preload reaches a certain extent [117, 118]. Ngo [39] studied the spindle properties in terms of preload from the perspective of oil film thickness variation. Matsubara [119] analyzed the interactions among stiffness, temperature rise and natural frequency of HSS by non-contact loading method, indicated the natural frequency increased with temperature rise and then decreased after temperature reached stable. Moreover, a hysteresis relation between temperature rise and natural frequency was uncovered. Kim [120] found the rotation accuracy of HSS was closely related to the spindle preload, which means the spindle rotation error varies with the preload, furthermore, the optimal preloads correspond to specific speeds respectively. Heavy preload can better guarantee the rotation accuracy of the HSS, unfortunately, serious heat generation and thermal deformation can cut down the accuracy either [121].

7.2.2 Influence Contrast of Pressure and Position Preload Approaches on HSS

Most literatures only concentrated on the constant pressure preload and its speed-dependent alteration during stiffness calculation, ignored the stiffness trait under the position preload, as discussed in the Refs. [122–124]. Only a few literatures have reported the performance differences of dynamic stiffness between preload mechanisms.

Assembly stress and centrifugal force have great influence on the stiffness of the two types of preloaded bearings, especially the position preload. Under low speed and small interference, the bearing stiffnesses obtained by the two preload methods don't change much [2]. Under constant pressure preload, when the preload changes from extremely light to heavy preload, the radial compliance of the spindle with low speed will drop by 50–80%, and the radial compliance of the spindle with high speed will reduce by 1.5–2.7 times; on the contrary, the axial stiffness will increase by 1.5–2.3 times under light preload, and the preload will remain constant under heavy preload [50]. Cao [8] comprehensively compared the stiffness and frequency response characteristics of HSS in different preload modes in terms of radial and axial preload, indicated the bearing stiffness in both modes would decreased when rotation speed rose, but the position preload could better maintain the system stiffness, as shown in Fig. 25 [8]. Moreover, he demonstrated the position preload was better than the constant preload to maintain the cutting stability. However, the change rule and influence factors of stiffness have not been studied in detail, and the TIP has been neglected. Zhang [2] emphasized the axial stiffness of the variable position preload was greater than the variable pressure preload when the same preload or axial negative clearance was applied. Under the position preload, the relative displacements of the inner and outer rings were restrained and the actual preload rose with the increase of the rotation speed. Compared with the constant pressure preload, the internal and external contact angles have same trends of gentle alteration, which even result in gentle increases of axial stiffness. Whereas, the position preload cannot be adapted to excessively high speed due to the temperature rise. Yang [116] analyzed co-influence of

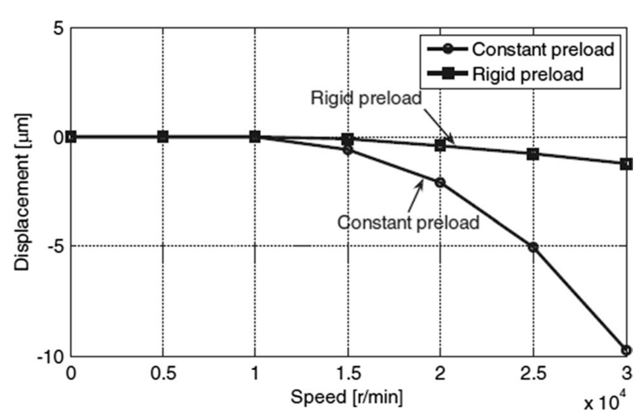

Fig. 25 Displacement variation of spindle end under different preload modes [8]

pressure-position mixed preload method on the vorticity frequency of HSS, claimed the critical speed of HSS couldn't been significantly risen by increasing the position preload value, while the stiffness difference of the preloaded bearing pairs can be declined.

7.3 Non-uniform Preload

The research on non-uniform preload mainly originated from Li et al. of Xi'an Jiaotong University. They adopted experimental and theoretical methods to study the effect of non-uniform preload manner on the behavior of HSS from multiple perspectives. When spindle rotates, the magnitude and direction changes of the bending moment caused by the non-uniform preload component can excite a significant position drift of the rotation center [106]. In static state, the non-uniform preload can reduce the shaft end displacement and ensure the axis orbit close to the initial position; in dynamic state, with the increase of rotation speed, the reasonable non-uniform preload can better compensate the shaft end displacement and move the shaft center trajectory to the initial position [125]. Cross stiffness is most significantly affected by non-uniform preload [126]. Compared with constant pressure preload, the difference in bearing temperature rise and vibration at low speeds is not obvious, while it is apparent at high speeds. The heat generation of bearing under non-uniform preload relates to the magnitude and direction of the equivalent torque, therefore, the equivalent torque with appropriate amplitude and direction can offset the external torque of bearing, reduce bearing heat generation and promote heat distribution more uniform [127]. However, a few problems still exist in this method: ① how to know the optimal preload distribution, otherwise, this method will turn into a factor affecting the spindle rotation accuracy; ② How to adjust the bearing with non-uniform preload in operation, because the bearing load varies in working condition.

7.4 Relationship Between Preload and Thermal Characteristics of HSS

Preload directly affects the contact stress between bearings ring and balls, but Pruvot [22] showed the bearing temperature rise was not positively correlated with the contact stress, which means the temperature was not high when the bearing was unstable under excessive contact stress, and vice versa. Ngo [39] found the contact angle and contact force only slightly changed under thermal effect if the bearing was preloaded by constant pressure, which might attribute to the contact angle and force were directly determined by the preload and bearing design parameters that can hardly altered by thermal effect. Therefore, it can be inferred that the thermal effect is ignorable when analyzing the contact angle and contact force, and thermal expansion has tiny effect on constant pressure preload. For variable pressure preload, thermal expansion can cause additional forces, thus the spring force is equal to the sum of the initial deformation force and thermal expansion force; for position preload, thermal expansion can cause additional displacement. Li [128] indicated that for preloaded bearings with lock ring structure, the total thermal expansion amount should be distributed for bearing seats and bearings if the value is known, and the bearing stiffness with nonlinear variation should be considered as well. However, for some symmetrical combinations, it was not necessary to find out the bearing stiffness because of the uniformly distribution of the thermal expansion. These combinations are common X-type, O-type, DB, DF configurations, and the distribution relations are shown in Fig. 26 [128]. where δ_z is the z direction displacement in the local bearing coordinate, δ_p is initial preload, ε_s is the thermal expansion in housing between the rear and front bearing, ε_h is thermal expansion of spindle between the rear and front bearing.

7.5 Preload Effect on Cutting Stability of HSS

7.5.1 Effect of Initial Preload

There is also a significant relationship between initial preload and cutting stability. Gao [129] emphasized that under low preload, the growth rate of cutting depth would be remarkably retard if a slight change occurred in the preload in a certain range. Therefore, the cutting depth limit can be treated as a criterion of optimal preload. On the one hand, increasing preload can increase the natural frequency of HSS and extend stability lobe diagram to high speed region; on the other hand, excessive preload can reduce damping and dynamic stiffness of tool tip, thus decrease cutting depth in stable cutting [130]. Hung [131] experimentally studied the cutting depth with respect to preloads which was divided as low, medium and high grades, revealed the ultimate cutting

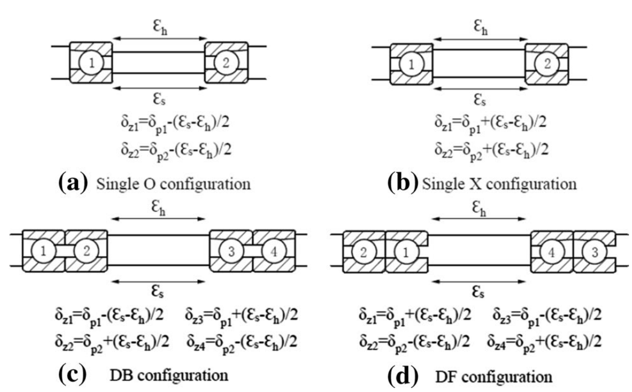

Fig. 26 Thermal expansion distribution [128]

depth increased with the increase of preload. However, the stability limit was affected by spindle mounting height and MT frame stiffness, which enhanced the coupling complexity of machining process and MT structure.

7.5.2 Influence of Thermal Induced Preload

Bearing stiffness accounts for 30% of spindle's stiffness and is deeply affected by the TIP. The TIP can reach 6 times of the initial preload, which is equivalent to 2.4 times of the static stiffness of the ACBB. Tu [26] showed the critical cutting depth decreased by approximately 15% when the bearing temperature rose from 30 to 40 °C, which may be due to the assembly interference variation caused by thermal expansions of outer ring and spindle shell and the decrease of bearing stiffness. Ozturk [132] showed the variable pressure preload has a positive effect on preventing bearing thermal expansion, bearing thermal seizure and improving bearing life, whereas, the dynamic characteristics and cutting stability of the HSS would be changed when the preload decreased. As shown in Fig. 27 [132], it is seen that compare with constant preload, the preload, tool tip stiffness and stability limit are improved as the speed increases under the condition of variable preload.

7.5.3 Effect of Centrifugal Induced Preload

For centrifugal force and gyro moment often appear at the same time, it is arduous to distinguish the single effect of CIP on cutting stability, accordingly, conflict opinions on the stability limit of high-speed cutting still exist. For example, Chen [101] didn't distinguish the effect of centrifugal force and gyroscopic moment on spindle characteristics. Movahhedy [133] indicated the gyro torque could decreased the stability limit at high speeds. However, Gagnol's [134] research demonstrated the spindle stiffness and stability limit increased at high speeds. Schmitz [135] obtained a similar conclusion with respect to a specific spindle system.

It can be inferred that the cutting stability would be better enhanced by increasing the preload, therefore, such method will boost the friction and accelerate the thermal growth and bearing failure [5]. Consequently, It is necessary to reduce the preload at high speeds for the sake of temperature rise, and to increase the preload to maintain the stable cutting limit. Unfortunately, this is a contradiction in itself.

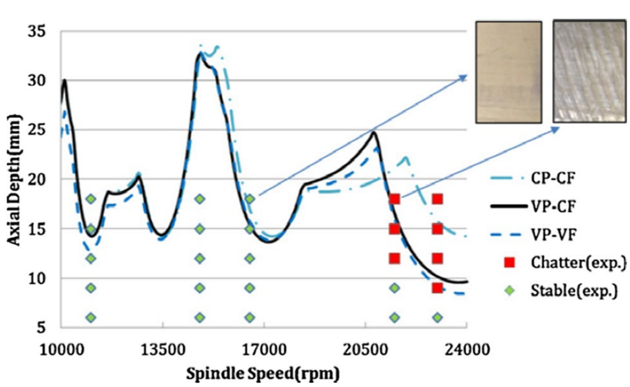

Fig. 27 Test results of cutting stability under CP and VP [132]. CP-constant preload; VP-variable preload; CF-constant force coefficients; VF-variable force coefficients

8 Conclusion

1. In summary, the current researches on the preload of HSS are still scattered, and systematic theoretical results haven't been established yet. A majority of bearing dynamic models focus on the modeling and stiffness calculation of single bearing, lack of in-depth research on preload mechanism, furthermore, the standardized calculation and selection method of optimal bearing preload haven't been formed. Most studies have attached importance to qualitative analysis instead of quantitative research from the influence of multiple factors on the preload, however, the actual requirement for preload must be a clear value. Therefore, one of the main research directions in the future is to rely on the precise thermal–mechanical coupling model for quantitative study, and to establish the corresponding relationship between preload and rotation speed (or other parameters) in terms of the multi-factor influence on the basis of precise load distribution calculation.
2. Compare with CIP, TIP has a greater influence on the HSS. However, TIP is tough to calculate accurately for the reason of thermal resistance and nonlinear thermal generation process. Because the TIP closely relates to the initial preload, rotation speed, cooling condition, lubricant viscosity et al., even significantly impact the performance of bearing stiffness and life, hence the research on bearing preload of HSS should focus on the calculation, transmission and distribution of TIP.
3. In the preload control mechanism, how to obtain the change amount of preload at high speeds in real time and how to adjust the preload are all important points requiring deep concern, which include accurate monitoring and measurement of preload, research of preload control method and design of preload device with rapid response capability, all of them are the main problems in the design stage. Separating CIP from TIP facilitates the formulation and implementation of control strategies, while real-time intelligent calculation and acquisition of optimal preload in sophisticated environments are the core issues of preload control.

4. Variable preload technology is one of the core technologies of intelligent spindle in the future. Although currently a handful of studies on active variable preload and corresponding devices have been reported, the instruments still have not received wide applied. Many designs are still in the research stage, for one reason, there are certain difficulties in theoretical research; for another, the performance, volume and price of the existing preload devices are hard to satisfy the requirements of HSS. Therefore, reduce the costs and launch mass production device with excellent performance as soon as possible is a great promotion to intelligent spindle.
5. The connection between preload and cutting stability should be emphasized. Balance the contradictable loop of "preload rise => stability limit increase => bearing temperature rise => TIP increase => bearing thermal lock => bearing fatigue life decline => stability decrease", hence optimize the preload to improve the spindle stiffness and cutting stability on this basis.

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Compliance with Ethical Standards

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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