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A New Approach Increasing the Rotational Accuracy of Ball-Bearing Spindle by Using Proper Bearing Positioning

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ABSTRACT

In order to improve the quality of a spindle unit it is important to increase its rotational accuracy. The rotational accuracy of a spindle unit can be defined as the stability or immobility of its spindle axis while rotating. Spindle rotation in the rolling bearings causes the disturbing influence, which leads to the oscillation of a rotation axis. The purpose of this study is to investigate the oscillation sources and find a way to decrease the runout without additional expenses. The main source of oscillation is the interaction between rolling bodies and ring races. The first oscillation source was the out-of-shape imperfection of inner bearing ring. The mutual compensation of oscillation by proper rings orientation was proposed, which sometimes allow to decrease the radial runout of spindle rotation axis by approximate 40% down. Also the outer ring harmonics were explored as the second oscillation source. The analysis shows the dependency between the number of rolling bodies and the outer ring race harmonics. The conclusion on the orientation of bearing cages and the bearing rings was made, which makes possible to obtain the optimal variant of their mounting in the spindle unit when the rotational accuracy of the spindle is maximal, and the spindle runout considerably less.

Key Words : rotational accuracy, ball-bearing spindle, bearing positioning

Nomenclature

D_m = diameter of the circle, which goes through the centers of bearing's balls
f = spectra of vibrodisturbance frequencies
j = number of each inner ring harmonic corresponding to the number of its waves
O_r = spindle rotation axis
P_y = radial force exerted on the spindle unit
z = number of rolling bodies in bearing
χ = number of harmonics of imperfections of inner races
λ = number of harmonics of imperfections of outer races
ξ = number of harmonics of Fourier-series expansion of ball radius
γ = angular step of rolling bodies
τ = contact angle of bearing
θ = bearing cage rotation angle
a_ξ = amplitude of harmonic ξ of ball radius
a_χ = amplitude of harmonics of imperfections of inner races
a_λ = amplitude of harmonics of imperfections of outer races
ω = spindle rotation frequency
ω_c = bearing cage rotation frequency

1. Introduction

Spindle units can be regarded as one of the most important parts in machine tools, since they determine the accuracy and productivity of machining. Currently, most of the spindle units used in the industry are running

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on rolling bearings, because they are cheap, reliable and simple in operation and maintenance. In the last 20 years, the development of spindle units was greatly influenced by the following factors: 1) development of new materials for cutting tools; 2) general increase of the accuracy of machining; 3) automation of machine tools based on the application of CNC technologies. Besides, the precision of machining for cutting machine tools is strongly affected by the rotational accuracy of a spindle unit. The rotational accuracy of a spindle unit can be defined as the stability or immobility of its spindle axis while rotating. Basically, accuracy is the value reciprocal to the imperfection, and in practice, we usually check spindle unit imperfection by checking its vibration and by measuring spindle axis displacements (vibration amplitudes or run-outs). There are several reasons for spindle vibration [12], among which we can point out imperfections of bearings [8], spindle out-of-balance, disturbances caused by the drive or the motor [12], etc. The vibration caused by out-of-balance is the simplest one, since it takes place at one frequency - the frequency of rotation, and can be improved by spindle balancing [9]. In this paper, we mainly concentrate on the rotational accuracy affected by the ball bearings imperfections. One of the factors, which characterizes spindle rotation accuracy, is the radial runout of spindle axis (regarded below as "rotation axis"), also known as radial motion error [10]. The radial runout is a sum of oscillation components with frequency different from the spindle rotation frequency, and directly affects the out-of-shape error and roughness of a machined surface.

It is well-known that the spindle rotation in the rolling bearings causes the disturbing influence, which leads to the oscillations of rotation axis. The main source of these oscillations is the interaction between rolling bodies and rings races. Indeed there are several reasons of generation of oscillation, but all of them have the same source – the form error of races in the bearings. The circumstance mentioned above leads to spindle oscillations with wide and dense spectra. In general the spectra of vibrodisturbance frequencies could be expressed by the formula [1]

$$f = | m\omega - kz\omega_c |, \qquad (1)$$

where ω - the spindle rotation frequency, ω_c – bearing cage rotation frequency, z – the number of rolling bodies in bearing; k and m = 1,2,3... [3].

A large number of research data [4] show that the low level of oscillations in high-speed spindle units could be obtained by increasing the bearings' manufacturing accuracy. Another way is to avoid the resonance with the careful selection of spindle's working frequency range of the spindle. Some constructive characteristics of bearings affect the rotational accuracy but in this paper this influence is omitted due to their insignificance. This paper will describe some practical methods, which improve the rotational accuracy of the spindle. These methods deal not with the increasing of the bearing manufacturing precision, but with the bearings proper and optimal positioning. This has a great importance for the spindle units manufacturing as it allows to obtain the same high results without using expensive high-precision assembly parts and machine tools.

2. The mechanisms of spindle axis oscillation

High-speed ball bearings have several sources of disturbances, i.e., the forces which produce vibration of spindle unit (SU) parts. These are:

1. Imperfections of macrogeometry of bearing's races, such as out-of-roundness, waviness, radial and axial run-outs, possible dents and scratches, etc.;
2. Imperfections of macrogeometry of the balls, which are similar to those of the races, plus possible difference of ball sizes;
3. Imperfections of microgeometry of races and balls, i.e. surface roughness (some of these imperfections protrude through the oil film generated between races and balls during normal operation, and produce collisions);
4. Variation of bearing stiffness while rotating (the radial stiffness depends on the position of balls with respect to the radial force vector);
5. Heterogeneity of elastic properties of races and balls;
6. Lubricant contamination;
7. Motion of cage;
8. Out-of-balance of spindle and bearing misalignments, etc.

However, when analyzing the precision bearings of precision SUs operating in favorable conditions, we can neglect some of these sources and save only two first ones. The theory of bearings having these imperfections is considered by Juravlev and Balmont[3].

The spectrum of imperfections of ball bearing's races and balls (the input parameters represented by the amplitudes of these imperfections $a_\lambda(\lambda)$, $a_\chi(\chi)$, and $a_\xi(\xi)$) and the spectrum of radial vibrodisturbances determined by the frequencies and amplitudes of harmonics (the output parameters). The spectrum of angular vibrodisturbances coincides with the spectrum of radial ones and differs in amplitudes by the multiplier $0.5 \cdot D_m \cdot \tan(\tau)$, where D_m is the diameter of the circle, which goes through the centers of bearing's balls, and τ is the contact angle of bearing. The spectrum of axial vibrodisturbances of ball bearing having imperfections of macrogeometry is also considered in [3].

The amplitudes of imperfections $a_\lambda(\lambda)$, $a_\chi(\chi)$, and $a_\xi(\xi)$ have a particular physical sense. The subscripts and arguments λ, χ, and ξ notify the numbers of harmonics of expansions of imperfections into Fourier series and attribute them to outer ring (λ), inner ring (χ), and balls (ξ). When the inner ring is first considered, the combinations of imperfections of races measured in the radial direction are shown in figure 1[11].

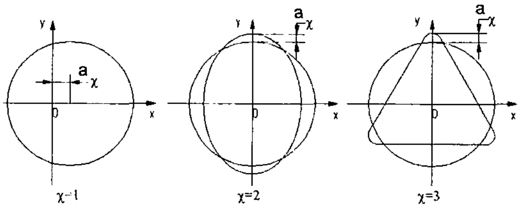


Fig. 1 Inner ring radial profile ($a_\chi(\chi)$)

Thus, for example, $a_\chi(\chi)(2)$ is the amplitude of the harmonic χ of bearing's inner race ovality; $a_\chi(\chi)(3)$ is the amplitude of the harmonic χ of bearing's inner race triangularity; etc. These imperfections can be measured using the round-meter gauges (for example, of Taylor & Hobson Co.). The summation of the components should be made as follows[11]:

$$a_\lambda = \sqrt{\left[\frac{\cos(\tau)-1}{\cos(\tau)} a_\lambda(1)\right]^2 + \left[a_\lambda(2)\right]^2 + \left[\tan(\tau) a_\lambda(3)\right]^2} \tag{2}$$

$$a_\chi = \sqrt{\left[\frac{\cos(\tau)-1}{\cos(\tau)} a_\chi(1)\right]^2 + \left[a_\chi(2)\right]^2 + \left[\tan(\tau) a_\chi(3)\right]^2} \tag{3}$$

The representation of imperfections of races and balls by Fourier series has a clear mechanical sense: harmonics $a_\lambda=2$, $a_\chi=2$, and $a_\xi=2$ correspond to the ovality of outer race, inner race, and balls (when averaged), respectively; $a_\lambda=3$, $a_\chi=3$, and $a_\xi=3$ - to triangularity, etc.; $a_\lambda=1$ and $a_\xi=1$ has no meaning; $a_\chi=1$ corresponds to the eccentricity of the inner race with respect to rotation axis, i.e. spindle out-of-balance (which is the imperfection of SU accuracy, not of the bearing); $a_\xi=0$ corresponds to averaged difference between diameters of balls. Further we will consider only the first type of imperfections – imperfections of macrogeometry of bearing's races.

The imperfection of races could be proposed as the sum of harmonics of amplitude-frequency spectra. Assume that the number j of each inner ring harmonic corresponds to the number of its waves, fitting the race: $j=2$ – ovality (two waves), $j=3$ – triangularity (three waves), etc. The analysis of amplitude-frequency spectra of races' imperfection allows us both to make a conclusion about the influence of spectra harmonics on rotational accuracy of the spindle and to find two mechanisms of oscillation generation.

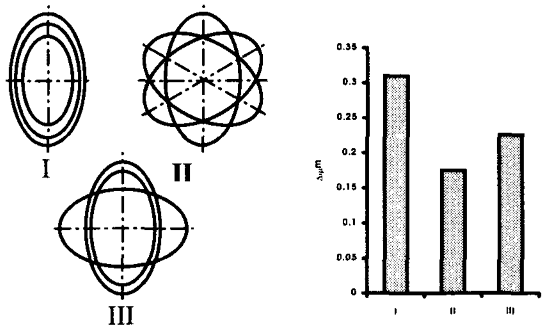
2.1 Decreasing vibration considering the force mechanism

The first one is the force mechanism; it reveals under the action of applied radial force P_y. When a spindle rotates, the race's imperfections force the preload in bearings and theirs stiffness to become variable by the angle of rotation. Thus the radial displacement of rotation axis, resulting from the bearings' stiffness at the force P_y, is changing and causes the oscillations of this axis.

The results of experimental researches[1] show that with the growth of force P_y the amplitude of axis oscillations increases; the main part (97%) of oscillations is formed by low-frequency components of vibrodisturbances, defined by harmonics in range $j=10$-15.

The proposed method of decreasing amplitude is based on the following observation: the imperfection may be conditioned by the presence of one harmonic, dominating by amplitude. This harmonic characterizes the ovality, triangularity and etc. Thus the radial stiffness of the bearing will be maximal in the direction of raised segments of race and minimal in lowered segments. If inner bearing rings on spindle are oriented in such a way that minimal and maximal stiffness directions will not coincide, the bearing stiffness will be equalized by the rotation angle.

The radial runout calculations for 3 different radial bearings of 436000 series [2], installed on the front part of spindle, was performed under the force P_y=100N, and ovality equal to 0.5 μm.



(a) (b)

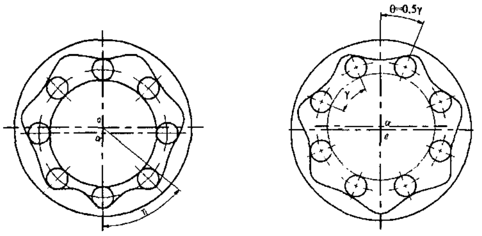
Fig. 2 Schemes of inner rings ovality orientation in the front SU bearing (a) and radial runout Δ of spindle axis rotation at each orientation (b)

Based on the bearing system theory [3] and mathematical model of SU [7], a series of experiments have been performed. In these experiments the radial axis runout was calculated as a difference between maximal and minimal displacements of the axis in several rotations as shown in Fig. 2(a).

Scheme I in Fig. 2(a) shows the inner rings ovality of three bearings oriented in the same direction; in scheme II the raised segments of the race are distributed evenly on the circle; in scheme III the inner rings are oriented in such a manner that the bearings on the ends have the same ovality, and middle bearing oriented perpendicular to them. In the Fig. 2(b) the calculation shows that the optimal orientation of inner rings corresponds to scheme II, which reduces the radial runout of spindle rotation axis approximately 40% down, comparing to scheme I.

2.2 Decreasing vibration considering the kinematics mechanism

This mechanism has connection with the harmonics of outer rings race imperfection; the number of these harmonics $j=kz\pm1$ [1, 11]. Assume that we have the spindle unit with bearing with eight rolling bodies (z=8) and outer ring has imperfection with harmonic j=7 as shown in Fig. 3.



(a) (b)

Fig. 3 The location of the spindle rotation axis Or caused by "resonance" harmonics of outer bearing race imperfection at the bearing cage rotation angle θ = 0 (a) and θ = 0.5γ (b)

In this combination of rolling bodies and harmonic waves the upper bodies will contact the raised segments of race and lower bodies will contact the lowered segments. Simultaneously the spindle rotation axis O_r is located in the extreme lowest position relative to the outer ring's axis O (see Fig. 3(a)). When the bearing cage rotates at the angle (in degrees) $\theta=0.5\gamma=180°/z$ (where γ - angular step of rolling bodies, see Fig. 3(b)), the rolling bodies, located in the upper part of bearing, contact the lower segments of race while bodies in lower part contact the raised segments; at the same time the axis O_r takes the extreme upper position.

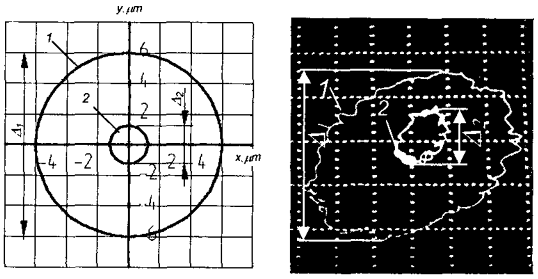
Hence at spindle rotation the rolling bodies and bearing cage together "copy" the harmonics of imperfection, and cause the rotation axis' oscillations with frequency divisible by $kz\omega_c$ frequency of rolling bodies movement along outer ring. That is why the harmonics caused such oscillations are called "resonance" harmonics. The appearance of such oscillations is possible even if the rolling bodies and races have absolute rigidity and no radial force is present. It means that they don't depend on force factors.

We propose the method which allows to reduce the spindle axis radial runout caused by "resonance" harmonics. The idea is the optimal orientation, when two bearings generate oscillations with amplitude in antiphase to each other. To implement this idea position of one bearing should correspond to the position shown in Fig. 3(a) and the second bearing to Fig. 3(b).

There are two possible optimal orientations of outer bearing rings:

1. When mounting SU, the outer rings of both bearings are rotated in such a manner that their "resonance" harmonics becomes mutually shifted by the angle $\Delta\alpha = 0.5T_j$, where T_j - the period of "resonance" harmonic. Since the "resonance" harmonics of both bearings are in antiphase, the oscillations of O_r axis, caused by them, are mutually compensated.
2. The bearing cage of one bearing is rotated relative to other bearing cage by angle $\Delta\psi = 0.5\gamma$. The resulting effect appears in antiphasing the oscillations of bearings.

Figure 4 shows the theoretical and experimental trajectories of spindle rotation axis in a radial plane. Radial runout Δ of rotation axis was defined as the difference between the maximum and the minimum shift of axis in the measured direction (for example, in the Y axis direction, as shown in the Fig. 3). Two variants of mutual orientation of bearing rings and bearing cages of front bearings were examined: 1) non-optimal orientation, when both bearings are oriented as shown in Fig. 3(a), i.e., $\Delta\psi = \Delta\alpha = 0$ and oscillations are cophased. 2) optimal orientation, when one bearing orientation corresponds to Fig. 3(a), and the second bearing orientation corresponds to Fig. 3(b), i.e., $\Delta\psi = 0.5\gamma; \Delta\alpha = 0$.



(a) (b)

Fig. 4 Theoretical (a) and experimental (b) trajectories of spindle axis rotation at non-optimal (*1*) and optimal (*2*) variants of mutual orientation of rings and bearing cages

Calculations displayed in Fig. 4(a) show that at optimal rings orientation the radial runout Δ_2 of axis is considerably less than radial runout Δ_1 at non-optimal orientation.

3. Experimental results and discussions

The proposed method of increasing rotational accuracy of the spindle was tested on a special SU model. To make the dominant effect of "resonance" harmonic of real bearings race over others, harmonic was modeled by the rollable deformation of outer bearings rings. The test stand was developed according to methodology described by Weck [10].

We consider a rotating shaft (spindle), the axis of which is perpendicular to a reference plane. If there is an error in the circular path, then the intersection of that axis with the reference plane will describe a curve. The detailed examination of such errors about the angle of rotation of the shaft is very complex. Hence only those errors, which are relevant to the particular application, are normally recorded.

Figure 5 shows the used method for measuring and simultaneously recording the relative motion of the axis of rotation, also known as radial motion error, or radial runout [5]. At the rear of the spindle a resolver measures the angle of rotation.

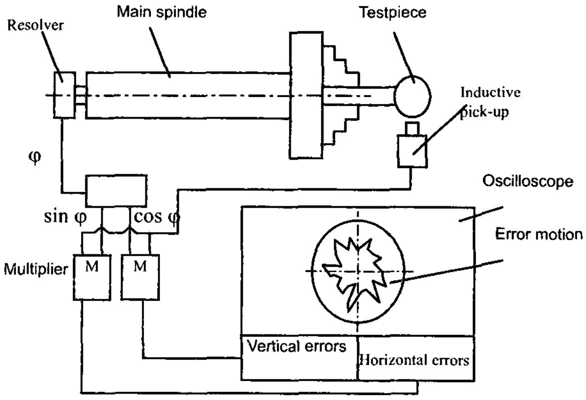


Fig. 5 Measurement of the relative motion of the axis of rotation (radial motion error) of a lathe spindle [5]

The circuitry connected to it produces an output, which is in terms of sine and cosine of this angle. A spherical testpiece held in a chuck is used to measure the radial motion error with the use of an inductive pick-up; both angular functions are modulated and error signals are then fed to the horizontal and vertical inputs of an x/y recorder or an oscilloscope. The eccentricity is measured only in the direction of the inductive pick-up, due to the particular method of setting. When such readings are taken on lathes, this direction is in line with the turning tool because this is the only direction in which any error will have an affect on the work accuracy.

The above mentioned methodology was used for testing the effect of proposed approach. Two series of experiments were performed. Fig. 2 shows the comparison chart for several variants of bearings orientations during the first series of experiments. The measured results show that optimal orientation of inner rings reduces the radial runout of spindle rotation axis approximately 40% down. Fig. 4(b) shows the results for the second series of experiments. The obtained data illustrates that Δ_2 runout was considerably less than radial runout Δ_1 . Therefore, varying the bearings orientation is possible to increase the rotational accuracy of the spindle.

4. Conclusions

The results obtained are summarized as follows. The purpose of our study was the improving the quality of designing of high-speed spindle units on rolling bearings. Another point was not to raise the price of the solution. We have studied and analyzed the factors that affect the rotational accuracy of the spindle from the bearing's side. The spectrum analysis of oscillations was performed, which allowed to distinguish two disturbance mechanisms – the force mechanism and the kinematics mechanism, caused by the imperfection of bearings.

When studying the first mechanism we have found that the rotation accuracy could vary drastically due to the way of mutual orientation of inner bearing rings, if these rings would have the same dominant harmonics (ovality, triangularity, etc.). Thus the mutual compensation of oscillation by proper rings orientation was proposed, which sometimes allow to decrease the radial runout of spindle rotation axis by approximate 40% down.

When studying the second mechanism, the spectrum analysis data of race imperfection of real bearings was made. This has the analysis shown the dependency between the number of rolling bodies and the outer ring race harmonics. The conclusion on the orientation of bearing cages and the bearing rings was made, which makes possible to obtain the optimal variant of their mounting in the spindle unit when the rotational accuracy of the spindle is maximal, and spindle runout considerably less. In test samples the radial runout in vertical and horizontal direction decreased by approximately 2 μm.

It is necessary to be noted that increasing of rotational accuracy is gained not by increasing the bearing manufacturing precision, but by their proper and optimal positioning. This has a great importance for the spindle units manufacturing as it allows to obtain the same high results without using expensive high-precision assembly parts and machine tools.

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