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Analysis of gear matching error of turntable

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Abstract

According to the characteristics of multi group gear fitting error of mechanical turntable, this paper firstly analyzes the different clearance elimination methods commonly used in turntable, and selects the double worm gear clearance elimination method, and determines that the basic reason for the method to replace the error is that the two gears have different eccentricity errors at different fitting positions. In the analysis, the gear rotation angle difference is 0 °, 90°, 180 °, 270° The eccentricity error of four positions is drawn as large period error and small period error, and synthesized into composite error. Considering a variety of errors, combined with the parameters of gear, the error model is simulated by Monte Carlo method in MATLAB software, and the preset fit angle of big gear ring and small gear is determined, so as to achieve the minimum error.

Keywords

Turntable, error analysis, Monte Carlo method.

1. Introduction

As one of the core components of machining center, large CNC turntable is the concentrated embodiment of high precision and high efficiency of CNC machine tools. As the fourth or fifth axis of the large machine tool, it controls the rotation of the large machine tool, and has the same status as the main motion of the machine tool. It not only improves the processing range and accuracy of the CNC machine tool, but also improves the production efficiency of the CNC machine tool. However, because the gear transmission naturally has certain errors, in order to improve the accuracy and reduce the cost, Therefore, many scholars have done a lot of research on it.

Wang Sheng[1] and others designed the clearance elimination structure of the turntable suitable for tk6513 NC planer horizontal milling and boring machine by analyzing the bearing performance and accuracy of the NC turntable; Chen Wenhua[2] predicted the error of the turntable gear through theoretical analysis, improved the accuracy of the turntable to a certain extent, and reduced the manufacturing cost. Wang xunlang[3] established the transmission error function of gear transmission error chain by analyzing the transmission error caused by various factors in the process of gear transmission and further studying the three main error sources. Wu Cisheng[4] derived the corresponding calculation formula from the eccentricity error of gear. Yang Kai and others took mch50 machining center as the research object, established the transmission accuracy model by considering the influence of multiple groups of errors, and verified the accuracy of the model by experiment.

This paper takes a certain type of mechanical turntable as the research object, introduces a variety of clearance elimination methods, and selects the most suitable method for in-depth research. When the gear rotates for one cycle, the large and small periodic errors of the gear are combined with the error parameters related to other gears, and the mathematical statistics method and Monte Carlo method are combined, Determine the best pre adjustment clearance angle of double gears.

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2. Gear error analysis

2.1. Selection of clearance elimination mode for rotary table gear

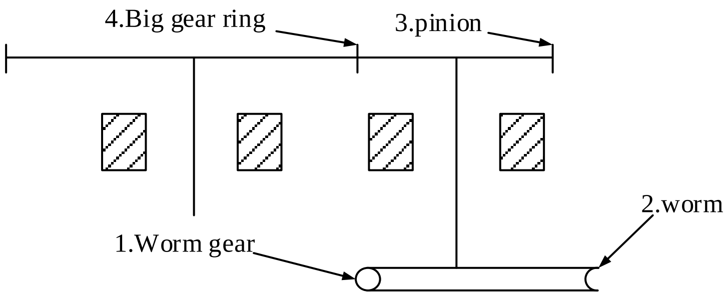

Figure 1 Gear transmission system

Through the Figure 1, the specific parameters are obtained. The motor transmits the power to the worm shaft through the coupling and synchronous toothed belt, and the power is transmitted to the gear shaft through the worm and worm gear pair. The pinion drives the big gear ring and the rotating table and workpiece on it to move and process. There are many kinds of gear clearance elimination methods, mainly the following.

1. Clearance elimination of double lead worm is characterized by simple structure and no redundant structure. It can change the position of worm and reduce the impact of wear on transmission accuracy. However, due to the fact that the specially manufactured worm will reduce the stiffness of worm tooth root, it is often used in occasions with small load.

2. Hydraulic motor clearance, it needs to add a set of hydraulic motor system in the structure to reduce the use of space. Its principle is to use the pressure difference of hydraulic motor to adjust and eliminate clearance. It is mainly used in medium and small load situations.

3.Clearance elimination of compound worm is characterized by simple structure. Its manufacturing method is that the worm is divided into two sections, one is made by hand, and the other is a real worm. The two sections mesh with the worm gear at different positions, and are mostly used for light load.

4.The clearance elimination of double worm requires that two worms are orthogonal distributed and connected by a bevel gear to mesh with different tooth sides of the worm gear. However, if the transmission chain of the worm changes, the clearance elimination effect will be affected.

5. The structure of clearance elimination of double worm gear is the worm that transmits kinetic energy through spline sleeve and the worm gear with opposite rotation angle, which can offset the influence of the worm and worm gear due to wear by adjusting their positions.

As the clearance elimination of double worm gear not only widens the gear tooth width, but also improves the meshing stiffness, the clearance elimination can be adjusted without fixing the driven worm. Therefore, the clearance elimination method of double worm and worm gear is selected. Its structure consists of two worm and worm gears with opposite rotation direction and equal rotation angle. The power is transmitted to the driven worm through the spline and spline sleeve through the worm connected to the motor. Because the rotation direction of the two worms is opposite, and the two small gears arranged in parallel are meshed with the big gear ring, the meshing clearance of the gears is eliminated.

When the worm and worm gear drive, the reverse clearance mainly depends on the clearance elimination system. Its stiffness is large because the worm and worm gear drive mesh is stable, so the transmission is stable, but it has a certain transmission error. The main source of its transmission chain error is large period error and small period error, which is caused by the error of gear and worm gear during processing and assembly.

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2.2. Large period error and small period error of gear meshing

If there is eccentricity error in gear, it will lead to transmission error. Gear meshing is divided into four parts, namely0°,90°,180°,270° the driving gear has an eccentricity, the eccentricity is, the driven gear is a gear without eccentricity error $OO'=e$, and there is no offset. The center distance between the driving gear and the driven gear is a fixed value $OO'=a$.

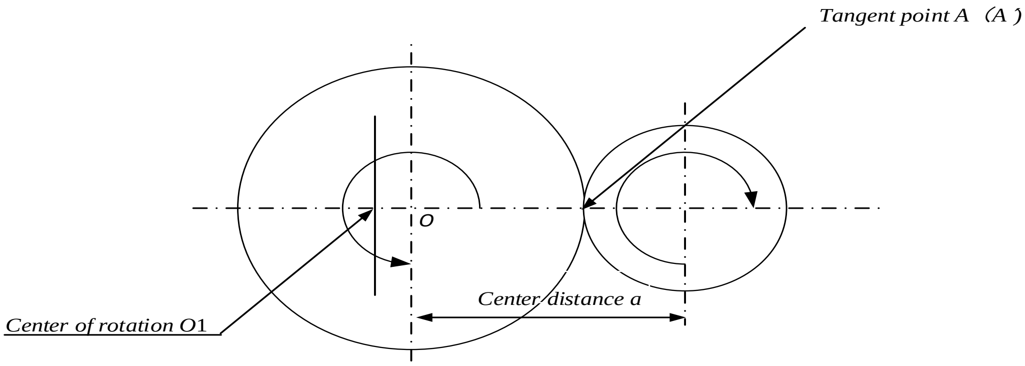

Figure 2 eccentric angle 0

When the angle is, the meshing points of the two gears are A and A′respectively.

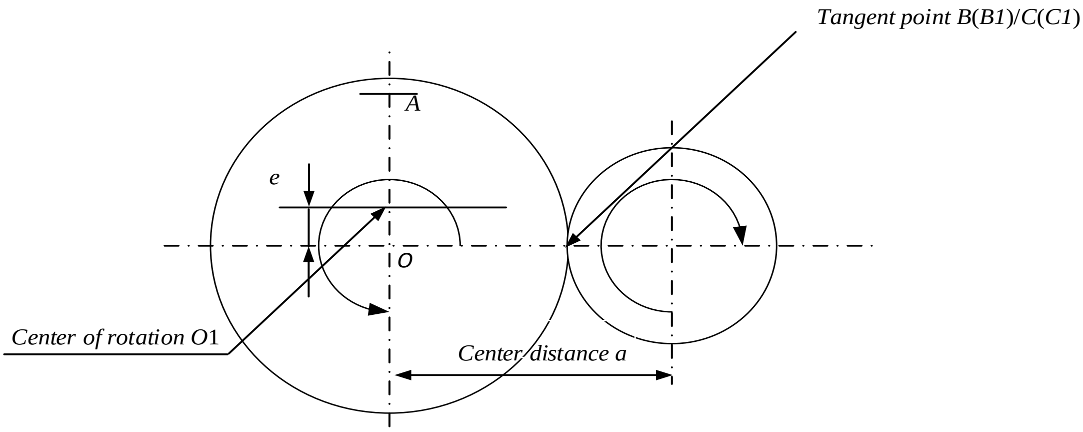

Figure 3 eccentric angle 90

When the driving gear rotates along the rotation center, figure 3 is obtained. At this time, with the eccentric rotation, there will be rotation error. The meshing point should be B, but it becomes C due to the eccentricity, resulting in a leading amount of transmission $BC \approx e$.

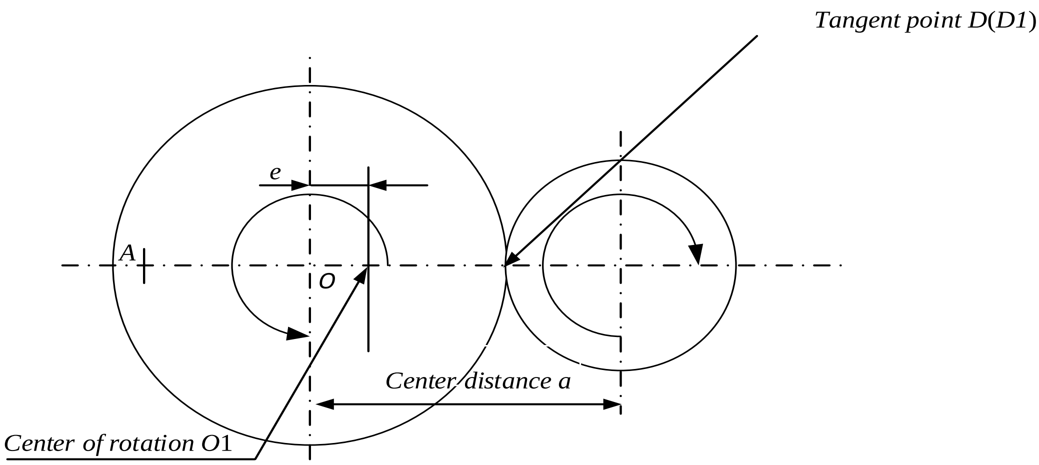

Figure 4 eccentric angle 180

When the driving gear rotates along the rotation center, figure 4 is obtained. It can be seen from 0°the figure that at this time, there is no eccentric error, and the meshing point is D.

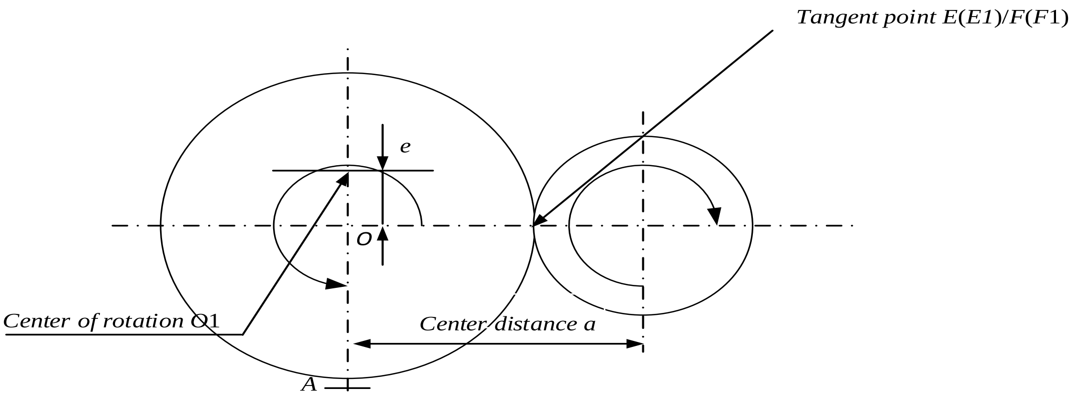

Figure 5 eccentric angle 270

After the driving gear rotates 90° along the rotation center again, the meshing point is E point instead of F point, so it is ahead, and its value is *EF=e*.

When the driving gear continues to rotate 90°, it returns to the original state. Therefore, it can be concluded that the meshing position of the eccentric gear on the pitch circle changes according to the sine function at different rotation angles esin(φ).

The large period error curve is drawn as follows:

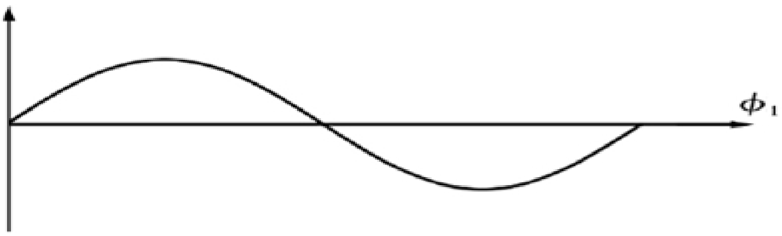

Figure 6 large period error

For some other inherent errors, such as pitch, tooth profile and tooth thickness, there will be periodic transmission errors, and small periodic errors will also be produced in each rotation cycle of a tooth. The curve is as follows:

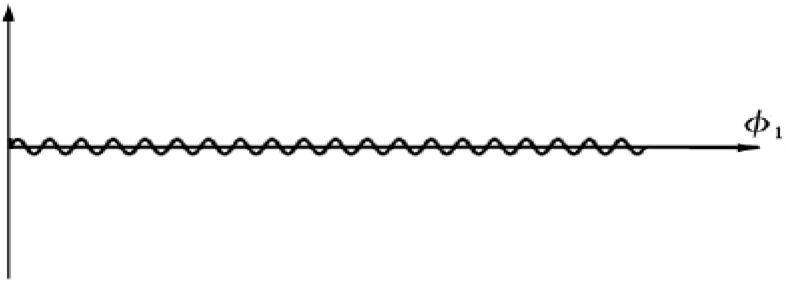

Figure 7 small period error

The combined error can be obtained by superposition of small periodic error and large periodic error:

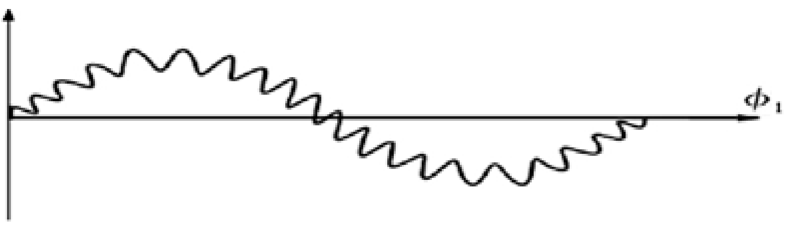

Figure 8 composite error

According to the mechanical design manual[5], the inherent position error of gear consists of five parts:

Table 1 pitch deviation

Name and code	definition
Single pitch deviation fpt	When the gear is rotating, the error of turning the angle of a tooth
Cumulative deviation of pitch fpk	Sum of errors when turning n gear teeth
Cumulative total deviation of pitch fp	When the rotating gear rotates for one circle, the sum of errors will be produced for all the angles

Table 2 tooth profile deviation

Name and code	definition
Total deviation of tooth profile Fα	It mainly makes the transmission smooth and affects the noise generation
Profile shape deviation Ffα	It mainly makes the transmission smooth and affects the noise generation
Tooth profile inclination deviation ±fHα	It mainly makes the transmission smooth and affects the noise generation

Table 3 tangential comprehensive deviation

Name and code	definition
Total tangential deviation F´i	When the gear rotates for one revolution, the maximum difference between the actual circumferential displacement and the theoretical circumferential displacement on the gear indexing circle
One tooth tangential comprehensive deviation f´t	When the gears are meshed and run for one circle, the tangential comprehensive deviation value within one pitch is rotated

Table 4 radial comprehensive deviation

Name and code	definition
Radial comprehensive total deviation F˝i	The difference between the maximum and minimum center distance when the gear rotates for one revolution
One tooth radial comprehensive deviation f˝t	When the gears are meshed and run for one circle, the radial comprehensive deviation value corresponding to one pitch is turned

Radial runout F_r: The measuring device is placed in each slot to measure the difference between the axis of the gear and the minimum radial distance.

Tooth profile error F_f: The minimum normal distance of two involutes which can contain the actual tooth profile.

Because the inherent position error of gear has a great influence on the gear error, which is more than 70%, there are two main evaluation methods：he first is a combination of f_{pt}, F_f and F_P, The second is made up of the combination of F'_i and f'_I the two. Because the latter is a comprehensive deviation, it is more accurate than the former to determine the transmission error, so the latter is generally used to calculate the transmission error, so this paper uses the combination of the latter to calculate.

According to the mechanical design manual[5], the accuracy of the pinion on the gear shaft calculated above is grade 5, and the coincidence degree can be known from the spur gear transmission ε=1 in the mechanical design manual.

$$F_i'=F_p+f'_t \tag{1}$$

$$f_i'=K(4.3+f_{pt}+F_\alpha) \tag{2}$$

because ε<4, $K=0.2\left(\dfrac{\varepsilon+4}{\varepsilon}\right)=1$, $fi'=4.3+f_{pt}+f_\alpha$.

Look up the table：d_{pinion}=60mm,m=2.5,f_{pt}=6.0μm,F_α=8.0μm,F_p=19.0μm, The parameters can be substituted by formula (1) and (2): f_i'=18.3μm, F_i'=37.3μm.

It can be seen from the above that the inherent position error of gear consists of two parts, namely, large period error and small period error, Because fi' and F_i' is a comprehensive coefficient, It is the coupling of many factors which have a great influence on the natural position error, and the error can be calculated more accurately[5]：

$$\Delta E^1=\frac{1}{2}\left(\Delta F_i'-\Delta f_i'\right)\sin\theta+\frac{1}{2}\Delta f_i'\sin\left(Z\theta\right) \tag{3}$$

Among：ΔE^1 is inherent position error； Z is number of teeth[5]； θ is phase angle of gear.

By analyzing the formula 3, we can get that the former part $1/2(\Delta F_i'-\Delta f_i')\sin\theta$ is the large period part, and the latter part $1/2\ \Delta f_i'\sin\theta$ is the small period part. These two parts have a great influence on the accuracy. They are both independent random variables and obey Rayleigh distribution, while the probability distribution on [0,2π] θ is uniform.

Because the distribution function of the two independent $1/2(\Delta F_i'-\Delta f_i')\sin\theta$ and $1/2\ \Delta f_i'\sin\theta$ variables is Rayleigh distribution, the distribution function can be deduced by probability：

$$F(x)=1-e\text{^}[-1/2(x/\eta)\text{^}2] \tag{4}$$

As 1-e^[-1/2(x/η)^2] a whole and a random variable, it is evenly distributed between intervals, which can be obtained by direct [0,1] sampling method：

$$R=1-e\text{^}[-1/2(x/\eta)\text{^}2] \tag{5}$$

In order to R and 1-R have the same probability distribution as on [0,1], the sampling formula is as follows:

$$X=\eta\sqrt{-2\ln R} \tag{6}$$

It can be known that x obeys Rayleigh distribution, so it is a random variable conforming to Rayleigh distribution.

Because $1/2(\Delta F_i'-\Delta f_i')$ obeys Rayleigh distribution, the value of should change randomly within the allowable tolerance, When the confidence is taken as 99.7%, it can be seen from the probability theory：

$$F\left[\frac{1}{2}\left(F_i'-f_i'\right)\right]=1-e^{\left\{-\frac{1}{2}\left[\frac{\left(F_i'-f_i'\right)/2}{\eta_1}\right]^2\right\}}=0.997$$

The values of distribution parameters are as follows：

$$\eta_1 = \frac{1}{2}\left(F_i^{'} - f_i^{'}\right) \Big/ \sqrt{-2\ln\left(1-0.997\right)} = \frac{F_i^{'} - f_i^{'}}{6.8} \tag{7}$$

Therefore:

$$\eta_1 = 2.79\mu m$$

Because the small period and the large period conform to the same distribution law, the distribution value is:

$$\eta_2 = \frac{f_i^{'}}{6.8} \tag{8}$$

$$\eta_2 = 2.65\mu m$$

2.3. Calculation of runout error of gear

In addition to the inherent position error, the runout error is another major reason for the transmission error. The main source of the runout error is the deviation between the designed rotation center and the actual rotation center, which makes the gear eccentric. The specific analysis is as follows, The reason for the runout error is that the gear hole and the shaft diameter have a gap, and the value is set as Δe_1, There are radial runout deviation Δe_2 and eccentric value of rolling bearing Δe_3 in the shaft installed with gear:

$$\Delta E^{''} = \sum_{i=1}^{3} \Delta e_i \sin\theta_i \tag{9}$$

Among: $\Delta E''$ is the sum of the transmission errors generated by the above three error generation methods: Δe_i is the above run out value, all of them satisfy normal distribution; θ_i is the phase angle of three error generation methods,which is evenly distributed in the region;

Because all Δe_i satisfy normal distribution, according to numerical analysis, its probability density function is:

$$f\left(x\right) = \frac{1}{\sqrt{2\pi\sigma}} e^{\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]} \left(-\infty \le x \le +\infty\right) \tag{10}$$

Through the method of transformation sampling, we can know that:

$$X = \mu + \sigma\sqrt{-2\ln R_1}\sin\left(2\pi R_2\right) \tag{11}$$

Sampling X is a random variable that obeys normal distribution in the computational domain. In the formula, random variable R_1 and R_2 obeys normal distribution, by using the same method, all probability density functions of Δe_i satisfy the uniform distribution in $f\left(x\right) = \frac{1}{2\pi}\left(0 \le x \le 2\pi\right)$, Therefore, the sampling formula is obtained by direct sampling: $X = 2\pi R$.

The random variables ([0,2π] and [0,1]) are uniformly distributed in their respective intervals. According to the principle of design 3σ, the qualified products must make the error meet this principle, so in Δe, the variation within the tolerance range must be met. When the confidence is equal to 99.7%, the following results are obtained:

$$\mu_i = 1/2e_i \ \sigma_i = 1/6e_i \tag{12}$$

At this time, the two kinds of errors are calculated, and the total transmission error of a single gear can be calculated as follows:

$$\Delta E = \Delta E^{'} + \Delta E^{''} = \frac{1}{2}\left(\Delta F_i^{'} - \Delta f_i^{'}\right)\sin\theta + \frac{1}{2}\Delta f_i^{'}\sin\left(Z\theta\right) + \sum_{i=1}^{3} e\sin\theta_i \tag{13}$$

2.4. Transmission error of meshing gear

In the transmission chain, the transmission error of the two gears is synthesized by meshing the two gears, and the transmission error of the big gear ring is converted into the angle error, and the error of the small gear is also converted into the angle error[6]:

$$\theta_f=\Delta E_{pinion}/r_2+\Delta E_{Big\ gear\ ring}/r_2 \tag{14}$$

Among:θ_f is the angular transmission error of big gear ring and small gear,r_1 and $r_2$are the indexing circle radius of pinion and big gear ring respectively.

2.5. Specific parameters of gear

Because the pinion is a gear shaft connected with the shaft, so e_1=0.

Table 5 parameters of big gear ring and small gear

project	pinion	Big gear ring
Number of gear teeth Z	24	144
Tangential comprehensive tolerance F_i'	31.8	54.3
Comprehensive error of one tooth tangential direction f_i'	16.8	21.3
Maximum clearance between gear and shaft e_1	0	53
Radial runout tolerance of gear Journal e_2	16	22
Radial runout tolerance of bearing e_3	10	25
Accumulated total deviation of gear F_p	15	33
η_1	2.20	4.85
η_2	2.47	3.13
Δe_1 distributed parameter μ_1,σ_1	0,0	26.5,8.8
Δe_2 distributed parameter μ_2,σ_2	8,2.6	11,3.6
Δe_3 distributed parameter μ_3,σ_3	7.5,2.5	16.5,5.5

Through the inquiry of national standard and mechanical design manual[5], the above parameters are obtained and tabulated.

Establish Monte Carlo method in MATLAB, input the parameters in the above table into the established Monte Carlo, generate random numbers[7] through the distribution law of probability theory, simulate the most likely results of transmission error, and make the calculated results into histogram. The results are as follows:

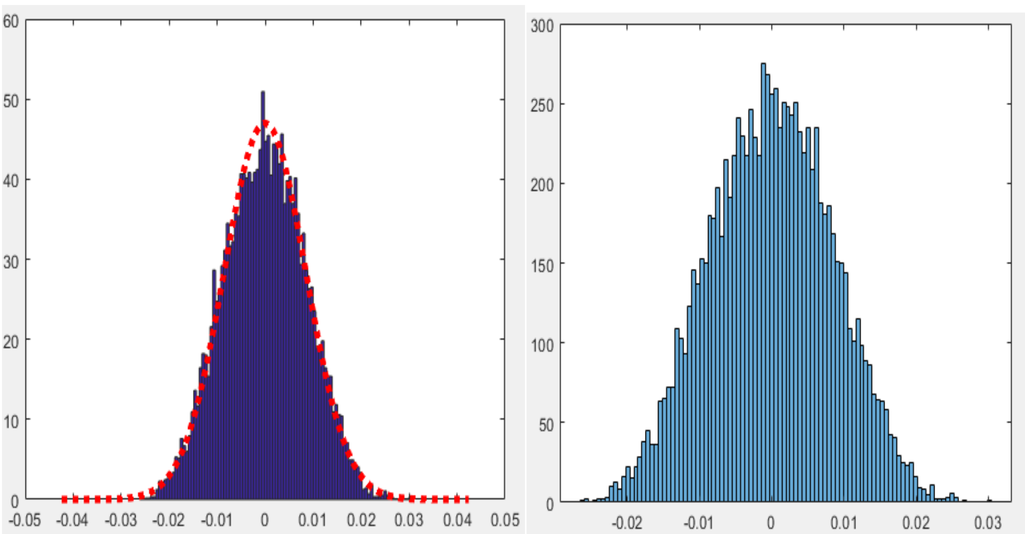

Figure 9 sampling distribution of transmission error 1 of turntable transmission system

2.6. Error of calculating gear clearance angle

In MATLAB, 10000 times are set to calculate the transmission error of the double gear transmission system, and the sampling distribution value of the transmission system is obtained as shown in the figure above. The histogram with confidence of 99.7% shows that the maximum error is $|\Delta\theta_{max}|$=93.6″ after 0.02% invalid points are removed, but the most concentrated part of the error is $|\Delta\theta_{Focus}|$=7.2 ″. Therefore, it can be further deduced that the error of each gear transmission is $|\Delta\theta_{Each\ tooth\ max}|$=3.9″, Similarly, $|\Delta\theta_{Each\ tooth\ focus}|$=3.9″.

2.7. Calculation of the optimum initial angle of misalignment for clearance elimination of double gears

By inquiring the empirical formula, we know that the best initial misalignment angle of backlash elimination is as follows：

$$\alpha=\frac{\Delta\theta}{Z}-\Delta\beta \tag{15}$$

Among：α is the initial angle of the misalignment of the two backlash gears,$\Delta\beta$ is the minimum oil film angle when the gear is meshed under normal lubrication, Because the meshing between the pinion and the big gear ring is a two-stage transmission mechanism, its speed is low and the motion is stable. So we can get:

$$\Delta\beta=2L/d_1 \tag{16}$$

Among:L is the minimum oil film thickness when the gear is meshed correctly, According to the mechanical design manual, the best value is L=0.003~0.005mm, take L=0.003mm,so $\Delta\beta_2$=0.06″, In order to ensure that the two gears can mesh correctly, the actual thickness of the oil film needs to be greater than both. Therefore, $\Delta\beta_1$ is selected as the calculation standard, and α can be obtained through the formula,so[8]:

$$\alpha_{max}=\Delta\theta_{Focus}/Z_1\text{-}\Delta\beta_1=3.36''$$

$$\alpha_{recommend}=\Delta\theta_{Focus}/Z_1\text{-}\Delta\beta_1=\text{-}0.24''$$

3. Conclusion

Through the selection of the clearance elimination method of the turntable, the clearance elimination method of double worm gear is determined. The error sources are analyzed as large period error and small period error. Then the two error generation methods are analyzed combined with the error parameters of the gear. The histogram of the gear meshing error is established by using Monte Carlo method, The error probability distribution based on statistical principle was observed intuitively, and the angle difference was determined by theoretical calculation to improve the machining accuracy.

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