The Adaptive Control of Accuracy at Centerless Grinding of Rolling Bearings

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Abstract. The method of adaptive control of accuracy at centerless grinding is developed. This method is based on statistical modeling of Monte Carlo and considers basic data of measurement of roundness of details. Results of application of the method for control of the accuracy of processing of rings of rolling bearings are given.

1. Introduction
Continuous increase of requirements to the accuracy of geometrical characteristics of details is observed in modern mechanical engineering. Therefore adaptive control of processing accuracy became actual. At centerless grinding the greatest difficulty is caused by receiving a precise form of a detail [1]. For precision details, for example rolling bearings, it is difficult to provide values of roundness within 0.0003-0.002 mm. It is known [2, 3] that a form deviation is usually a result of violation of a trajectory of the relative movement of a detail and a tool. For rolling bearings' details except traditional error fraction (elastic movements, thermal deformations, vibrations) the significant contribution is made by a hereditary drawback of geometry.

Centerless grinders work in an automatic cycle and represent poorly governed systems. The organization of control for output parameters by means of feedback is difficult. Such machines on motionless support as the models SIW-5 and SWaAGL-50 (Germany) have limited opportunities for geometrical adjustment change and cutting modes. On the other hand static control for the size of such machines is more difficult because of nonrigid kinematic communications and power short circuit of contact between a detail, a tool and basing machine elements. The arising errors of basing depend as on parameters of adjustment of machines as on an initial error of details' geometry.

2. The method of adaptive control of accuracy at centerless grinding
The main objective of processing accuracy control on grinders is to provide the maximum correction of roundness. The solution of this task is carried out on the basis of optimum adjustment of the machine within the parameters setting the relative provision of a detail 1, a grinding wheel 2 and basing elements – faceplates 3 with a magnetic clip and two motionless support 4, 5 (figure 1). The main complexity is that deviations of a detail's form have stochastic character and there is no real possibility for the best adjustment.

Statistical simulation (the Monte Carlo method) may be used here [4]. In setting up a machine tool with minimum basing error, this approach involves simulation of the stochastic input data (shape deviations of the blanks) and multiple implementation of the analytical basing model. Simulation yields probability characteristics whose numerical values are equal to the results of solving the
determinate problem. Statistical analysis of a series of basing-error values permits the determination of the influence exerted on the machining accuracy of a batch of blanks by the setup parameters of the machine tool.

![Figure 1](image)

**Figure 1.** Calculating model at centerless grinding.

The corresponding algorithm is shown in figure 2. The initial data include the blank parameters \(BP\) (radius \(r_0\) of the mean profile circumference; number \(p\) of harmonics; distribution parameters and boundaries of the ranges of the amplitudes \(a_n\) and initial phases \(\varphi_n\) of the harmonics), the setup parameters \(S\) of the machine tool (the angle \(\alpha\) between the motionless bearings), and the number \(m\) of blanks in the batch. The variation of \(\alpha\) in optimization is bounded on the basis of the machine tool characteristics.

In the first stage, the geometric shape deviations in the batches of blanks are simulated. First, sequences of uniformly distributed numbers random \(z_i\) are generated for each blank \(j\), as a function of the number of profile harmonics \((i = 1, m\)\). The values of \(z_i\) are converted to the required distribution law for the amplitude \(a_n\) and initial phase \(\varphi_n\) of each harmonic. As a result of summation, the profile \(r_j\) of the blank is formed [5, 6].

The cross section of the blank with periodic shape deviations is described by a trigonometric polynomial of the form

\[
r = R + \sum_{n=2}^{p} a_n \cos(n\varphi - \varphi_n) ,
\]

where \(R\) is a Least Squares Circle radius; \(a_n, \varphi_n\) is the \(n\)-harmonic’s amplitude and epoch angle; \(p\) is a maximum number of harmonics considered; \(\varphi\) is a polar angle.

The generation of random numbers with a specified distribution is based on the inversion method [4]. In this method, a sequence of random numbers \(z_i\) uniformly distributed in the interval \([0, 1]\) is formed and then transformed:

\[
x_i = F^{-1}(z_i) ,
\]

where \(F^{-1}(z_i)\) is the inverse of the distribution function of the random quantity \(x_i\).

Experiments show that the amplitudes \(a_n\) of the harmonics are best described by a \(\beta\) distribution, while the initial phases \(\varphi_n\) are best described by an equal-probability law.
The probability-density function of the $\beta$ distribution takes the form
\[ f(x) = \frac{\Gamma(\eta + \mu)}{\Gamma(\eta)\Gamma(\mu)} x^{\mu-1} (1-x)^{\eta-1}, \] (3)
where $\Gamma$ is a gamma function; $\eta$ and $\mu$ are the parameters of the $\beta$ distribution.

The distribution function of the initial phases of the harmonics takes the form
\[ F(x) = \frac{e^{bx} - e^{cx}}{e^{b} - e^{c}}, \] (4)
where $b$ and $c$ are the boundaries of variation of $\phi_n$.

Experiments show that there are strong correlations between the amplitudes of some harmonics; these must be taken into account in simulation. Therefore, for random errors $x_1$ and $x_2$ with different distribution functions $F_1(x_1)$ and $F_2(x_2)$, mathematical expectations $m_{x1}$ and $m_{x2}$, and mean square deviations $\sigma_{x1}$ and $\sigma_{x2}$, it is expedient to switch to the random quantities $z_1$ and $z_2$ uniformly distributed in the interval $[0, 1]$, by means of the transformations
\[ z_1 = F_1 \left( \frac{x_1 - m_{x1}}{\sigma_{x1}} \right); \quad z_2 = F_2 \left( \frac{x_2 - m_{x2}}{\sigma_{x2}} \right). \] (5)

The linear correlation coefficient is [7]
\[ k = \frac{12}{n-1} \sum_{i=1}^{n} \left( z_i - \frac{1}{2} \right) \left( z_{i+1} - \frac{1}{2} \right). \] (6)

This simplifies the generation of correlated random quantities with different distributions and eliminates the dependence of $k$ on the form of these distributions.

In the second stage, we calculate the basing error for each blank from the analytical model [7]. Then we find the basing characteristic $K_j$ for each blank $j$ in the batch.

The third stage is statistical analysis of the $K$ values calculated for all the blanks in the batch. As a result, we obtain the mathematical expectation $M_K$ and the mean square deviation $\sigma_K$. Then, we optimize the setup parameters $H$ of the machine tool so as to minimize $M_K$ and $\sigma_K$.

Analysis of the results obtained by the proposed simulation algorithm show (figure 2) that $K$ is best described by a normal or log-normal distribution. (The log-normal distribution appears when there is a

![Figure 2. Simulating algorithm for machine-tool setup (Monte Carlo method).](image)
correlation between groups of harmonic amplitudes.) The probability-density function is uniquely
determined by $M_K$ and $\sigma_K$, which are selected as the parameters to be optimized. Numerical
experiments indicate that $M_K$ and $\sigma_K$ are a minimum at the point corresponding to a specific setup
angle $\alpha$.

3. Results of experimental research

The proposed method is verified at Saratovsky Bearing Plant (EPK Saratov) in grinding bearing
rings 5-830900AE1.02 on SWaAGL-50 machine tools. The tolerance for noncircularity of the annular
channel is 0.0012 mm; the surface roughness $Ra = 0.32 \mu m$. In grinding the wheel and the blank move
in the same direction, at speeds of 35 m/s and 35 m/min, respectively.

The data of monitoring of roundness of a ring of the bearing received during 2010 are given in
figure 3. Correction coefficients (the roundness relation before and after fair grinding) for average
value of $K_x$ and a standard deviation of $K_\sigma$ are presented. The vertically shaped line shows processing
time border at standard and adaptive adjustment of the machine.

The optimum adjustment of the grinder has stabilized the average value and the standard deviation
of roundness in party irrespective to the initial error of details' form. Dimensionless coefficients of
correction of $K_x$ and $K_\sigma$ increased accordingly from 0.6 – 1.4 to 1.1 – 2.75. Along with that a stable
decrease of a standard deviation of roundness on an absolute value is noted. These results are
consistent with the data in Refs [8. 9].

![Figure 3. Monitoring of roundness of a ring of the bearing.](image)

4. Summary

Application of adaptive control of accuracy on the basis of statistical modeling opens new
opportunities for adjustment of centerless grinders. Further development of grinders is connected with
creation on their basis mechanotronic systems for ensuring optimum processing of details of rolling
bearings.

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