Automated measurements in process monitoring system in bearing production

A A Ignatiev, B A Dobryakov, C A Ignatiev, A Kazinsky, T G Nasad and I P Nasad
Yuri Gagarin State Technical University of Saratov, 77, Politechnicheskaya str., Saratov, 410054, Russia
E-mail: atp@sstu.ru

Abstract. The methodological foundations of the use of automated measuring systems in the monitoring system of the technological process of manufacturing parts of bearings are considered. In addition to the means used to control the accuracy of manufacturing of bearing rings, the use of vibration measuring instruments to assess the dynamic quality of each grinding machine, automated eddy-current quality control devices for the surface layer of parts, and an active dimensional control system, the functions of which are expanded by controlling the speed of the removed stock, are considered. All information is processed in a monitoring system and used to improve the quality of bearing parts.

Ensuring the competitiveness of the products of the bearing industry both in the domestic and international markets is associated with the introduction of a product quality management system (PQM). A special place in PQM is given to the monitoring system of technological process (MSTP), which functions are the control of manufactured parts, equipment diagnostics and product quality management, based on a thorough analysis of the measurement results of a complex of technological process parameters (TP) [1]. To create an effective MSTP, methodological foundations aimed at its expedient organization, justification of the structure, complex of technical and software solutions are needed. Data on the real technical condition of equipment and TP parameters are generated by means of monitoring machines, processing modes and quality of parts, with which measurements of determining parameters are carried out in manual, automated or automatic modes. Data processing and presentation of results in a form convenient for decision-making is carried out by computers.

The reliability of bearings under operating conditions, especially in aviation, automotive and other industries related to machine and instrument engineering is substantially connected with the quality of the final grinding of bearing rings, which mainly determines the quality of raceways (dimensional accuracy and surface layer quality). Stochastic processes in the cutting zone during grinding (thermal, power, vibration, and a number of others) determine deviations of the macro- and microgeometric accuracy parameters, a change in the physicomechanical characteristics of the surface layer and the appearance of various defects. The studies of domestic and foreign authors have revealed a fairly wide range of factors affecting the quality of the polished surface. In the works of D.G. Evseeva, A.V. Queen, L.N. Filimonova, G. B. Lurie, L.V. Khudobin and other authors the effect on the quality of the treated surface of various parameters of TP is examined. However, in connection with the intensive automation of machining processes, based on the introduction of high-performance automated metal-cutting
machines (AMC) and new tools, the task of monitoring the technological process in serial production arises.

The formation of accurate and reliable results of measurements of various parameters of AMS and parts in MSTP are based on metrologically certified equipment and correct methods of processing measurement data. Special algorithms and mathematical software developed for this implement high-performance data processing and prompt decision-making on the quality management of TP.

The most common method of controlling the quality of the rings during grinding is the use of active dimension control (AC), in which AMC control system continuously monitors the removed allowance, as well as postoperative means of monitoring the accuracy characteristics of the machined surface of the rings. In addition to the specified types of control and a reasonable choice of the technological regime within the framework of MSTP, it is advisable to use additional parameters for control. Automated measurement of parameter values associated with the dynamic quality of the machine and with the quality parameters of the surface layer of the rings should be used to create additional information channels for controlling the machining process [2, 3]. When implementing MSTP, it is necessary to take into account the available control tools in the grinding AMC and those tools that should be used for multi-parameter control (built-in and external controls) (figure 1).

Figure 1. Solving monitoring tasks with built-in and external controls.

First, it should be noted that an important factor affecting the accuracy parameters of parts and the physicomechanical characteristics of the processed surface layer is a dynamic quality of AMS, estimated by the characteristics of vibroacoustic (VA) vibrations [4-7]. It changes both in the process of functioning as the operating life increases, and when the values of the parameters of the cutting mode vary, therefore, in the manufacture of high-precision parts for machine and instrument engineering, it is
especially important to evaluate the real dynamic quality of the machines. For this, a measurement of the level of VA vibrations of the nodes of the forming subsystem is used, to which the spindle assemblies (SA) of the part and tool should be attributed primarily. Vibrations of these nodes most significantly affect ellipticity, waviness and roughness of the machined rolling surface, and also contribute to a change in the structure of the surface layer, which reduces the reliability of bearings [2, 3].

It is preliminary advisable to build and analyze the mathematical model of AMS as a complex dynamic system (DS), which will allow estimating the spectrum of its VA oscillations. It is advisable to consider the transfer function [2] as a mathematical model of the machine tool of DS, and in the production environment, the vibration levels of the grinding wheel of the abrasive wheel \( x(t) \) and SA of the part \( x_A(t) \) should be taken under production conditions as controlled output variables that allow evaluating the dynamic quality of the machine. The model of grinding AMS by V.N. Mikhailievich [8] is accepted as a basis, which has been amended to take into account the dynamic characteristics of SA circle and SA parts [2,3]. For the regulatory action, the movement of the grinding wheel \( v_c \), was adopted, and for the output variable of the object, the radial component of the cutting force \( F_r \) was adopted. In this case, the transfer function of the DS will have the form

\[
W_p (p) = \frac{1}{p} \left( 1 - e^{-\frac{p \beta \tau_d}{\gamma_d}} \right) \frac{K_{PE3}}{1 + K_{PE3} \left( 1 - e^{-\frac{p \beta}{\gamma_d}} \right)} \left[ W_{\beta} (p) + W_{\mu} (p) \right],
\]

where \( K_{PE3} \), \( \beta \) are coefficients that determine the cutting process; \( \tau_d \) is part turnaround time.

The recorded oscillations of DS are determined by its amplitude-frequency characteristic (AFC), for the calculation of which the expression for \( |W(j \omega)|^2 \) obtained from formula (1) is used

\[
|W(j \omega)|^2 = \frac{(h_{\beta} + h_{\mu} - h_{\beta} T_{\beta}^2 \omega^2)^2 + 4 h_{\beta}^2 \gamma_{\beta}^2 T_{\mu}^2 \omega^2}{(1 - T_{\beta}^2 \omega^2)^2 + 4 \gamma_{\beta}^2 T_{\mu}^2 \omega^2}.
\]

where \( h_{\beta}, h_{\mu} \) are coefficients due to the static stiffness of the individual elements of SA; \( T_{\beta}, T_{\mu} \) are time constants due to the natural frequencies of the individual elements of SA; \( \gamma_{\beta}, \gamma_{\mu} \) are relative damping coefficients of individual elements of SA,

\[
\gamma = \gamma_{\beta} + 0,5K_{PE3} \gamma_{\mu} (h_{\beta} + h_{\mu}) T_{\mu}^{-1}.
\]

The frequency response model built on a computer in the Matlab environment contains two frequency ranges corresponding to the eigenfrequencies of SA circle and SA of the part, which is consistent with the experiment [6, 7]. These frequency ranges are further used for VA control of the machine dynamic quality.

When assessing the quality of processing of the outer rings of bearings of various types, measurements of VA vibrations were performed on circular grinding machines of SWaAGL-50 model at JSC EPK-Saratov. To control VA vibrations, VShV-003M2 vibration meters and a computer were used. Sensor signals were recorded in the frequency range 1 ... 4000 Hz. The results of measuring the waviness and ellipticity of the bearing rings on the Talyrond-73 circular meter are shown in Table 1. The data in figure 2 indicate that VA level of vibrations of machine No. 166 is higher than that of
machine No. 436, which implies that the geometric accuracy of the machined surface correlates with the level of vibration DS.

### Table 1. The accuracy of the processing of rings on machines of the model SWaAGL-50.

| No. of machine | Type of a ring | Waviness, micron | Ellipticity, micron |
|----------------|----------------|------------------|---------------------|
|                |                | pre-treatment     | final processing    |
| 436            | 208.02         | 3.44              | 0.68                |
|                |                | 1.22              | 0.92                |
| 166            | 308.02         | 3.24              | 2.87                |
|                |                | 1.68              | 2.20                |

The real DS of the machine contains a large number of links which vibration frequencies must be taken into account when excited by a “flat noise” signal; therefore, the recorded spectrum of VA vibrations has a more complex composition. Under operating conditions, it is advisable to formulate numerical estimations of the dynamic quality of AMS, for example, use the integral estimations of the spectra of VA vibrations of the form of DS [9]

$$I_\alpha = \int_{1}^{\omega_2} S(\omega) d\omega,$$

where $\omega_1$, $\omega_2$ is the lower $\omega_1$ and upper limits of the frequency range of the measured VA vibrations of the DS.

From a practical point of view, the use of autocorrelation functions (ACF) of VA oscillations and their integral estimations [2] is quite convenient for the analysis of stochastic oscillations in DS. In this case, it was found that the lower the integral ACF estimations, the higher the dynamic quality of the machines. For a similar purpose, the use of integrated spectrum estimations is also of scientific interest.

In most cases, for grinding machines, experimental ACFs are approximated by the formula

$$K(\tau) = K_0 e^{-\alpha \tau} \cos \omega_0 \tau,$$

where $K_0$ is a value of ACF at $\tau = 0$, which without loss of generality can be taken $K_0 = 1$; $\alpha$ is the damping coefficient, $\omega_0$ is frequency of damped oscillations of the ACF.

The spectral density (or simply spectrum $S(\omega)$) is related to ACF by the known relation

$$S(\omega) = \int_{-\infty}^{\infty} K(\tau) e^{-j\omega \tau} d\tau.$$  \hspace{1cm} (5)

In view of formula (4), from expression (5) we obtain

$$S(\omega) = \frac{2\alpha(\omega^2 + \omega_0^2)}{[\alpha^2 + (\omega - \omega_0)^2][\alpha^2 + (\omega + \omega_0)^2]].$$

To calculate the integral estimate from expression (6), we expand its right-hand side by the method of indefinite coefficients:

$$S(\omega) = \frac{\alpha}{\alpha^2 + (\omega - \omega_0)^2} + \frac{\alpha}{\alpha^2 + (\omega + \omega_0)^2}.$$  \hspace{1cm} (7)

To identify the tendency for the integral spectrum estimation to change with increasing ACF attenuation coefficient, the derivative with respect to $\alpha$ is calculated and $dI_\alpha(\alpha)/d\alpha < 0$, is determined, i.e., the integral estimation is monotonically decreasing, as well as the integral ACF estimation and the vibration coefficient, known from theory of automatic control (Fig. 2, Fig. 3).

A comparative analysis of processing accuracy and integral estimations for SWaAGL-50 machines shows their correlation (figure 2).

Similar results were obtained on AMS of another model. When analyzing the processing quality of ball bearing rings, vibration measurements were performed on four SIW-5 model internal grinding machines. Integrated estimations of the spectra were used as informative characteristics of dynamic quality (figure 3). From the measurement results it can be seen that the value of the quality parameter “waviness” of the raceway is minimal for machine No. 395, which has the lowest values of the integral spectrum estimations.

Thus, the considered estimations can serve as an assessment of the dynamic quality of machines.
Figure 2. Measurement results on SWaAGL-50 machines: a - values of ellipticity (1) and waviness (2) of the rings (the minimum and maximum values are highlighted in color in the columns); b - the values of the integral estimations of the auto-spectrum of the oscillations of the support ring (3), values of integral estimations of the mutual vibration spectrum of the support of the ring and SA of the circle (4).

Figure 3. The value of the integral estimations of the spectrum, the indicator of the oscillation of the DW and the undulation of the raceways of the rings (average value of 5 rings, permissible value of 2 μm) when processing on SIW-5 machines: ACF - autocorrelation function; 1 - Integral spectrum estimate; 2 - Waviness; 3 - Integral evaluation of ACF.

The second additional parameter for evaluating the quality of rings in MSTP is the assessment of the heterogeneity of the surface layer of bearing rings by the eddy current method. At JSC EPK-Saratov bearings are inspected using computer-controlled PVK-K2M model automated instruments (figure 4). The eddy current sensor scans the rolling surface of the ring. Its signals are processed by a computer and visualized [10].

Figure 4. General view of the automated eddy current control system PVK-K2M
The instrument software provides for the identification of major defects in the surface layer of raceways with a depth of 30 ... 40 microns. The detection technique is based on comparing the images of defects of controlled parts by informative signs with the images of defects of standard parts (defect-free and having known defects detected by other known non-destructive testing methods). Assessment of the heterogeneity of the surface layer is carried out in points (from 2 to 5) and is associated with the depth of the defect [10].

Examples of typical defects that occur during grinding of bearing rings and detected by the device are shown in Fig. 5. The control time of one ring depends on its size (10 ... 40 s). The transition to measuring a ring of another size is provided by the selection of the appropriate program.

The results of eddy current testing reflect differences in the state of the surface layer of rings with and without defects and correlate with the dynamic quality of the machines. In this case, an increase in the quality of the rings is achieved by changing the grinding mode, by tightening the requirements for the quality of the workpieces and the technical condition of the machines, so that the surface layer of the raceways is uniform.

The PVK-K2M device is certified as a means of non-destructive testing. The company has developed a methodology for metrological verification, certified standard samples used for instrument calibration with artificial defects that are formed by laser radiation. According to the results of metrological certification, the PVK-K2M device is included in the State Register of Measuring Instruments under No. 26079-03. The device identifies defects with a minimum depth of 5 microns and a width of 200 microns. A comparison of the values of the accuracy parameters (ellipticity, waviness) of the controlled surfaces and the results of eddy current control shows that a certain relationship is observed between them, which implies that such control reveals the disorder of the technological process, which leads to a decrease in the accuracy of parts.

![Figure 5. Eddy current images of rolling surfaces of bearing rings: a - non-uniform surface; b – crack.](image)

The use of devices made it possible to improve the quality of the processing of raceways of bearing rings due to the adjustment and repair process of equipment, which gives a relatively large heterogeneity of polished surfaces. The refinement of scientific software (SS) made it possible to realize automated recognition of the main defects of the surface layer of the rings [10], for example, using wavelet analysis of the eddy current sensor signals, and these data are transferred to MSTP database, which creates the conditions for the operational control of TP and allows guarantee the quality of grinding rings.

As the third additional quality control channel in MSTP grinding AMCs, an AK device should be adopted, the functions of which are expanded to directly control processing and ensure a given ring quality. The use of AK of the current allowance provides the dimensional accuracy necessary for the selective assembly of bearings, however, the variation in the size of the workpieces leads to a decrease in the uniformity of the surface layer and the possible occurrence of defects (for example, burns). Improvement of AK devices based on the introduction of microprocessors allows you to additionally
control the level of vibration in DS and the speed of stock removal. Measurement of vibration of the DS allows controlling not only the grinding process itself, but also the dressing circle [2, 3].

It is known that in real production, the control of the feed of the wheel to grinding machines is programmed to provide the parameters of the working cycle. With a stochastic change in the stock allowance, variations are observed in the rate of metal removal, and, accordingly, the level of VA oscillations of DS, which leads to a variation in the quality of the raceways of the rings. The control of the feed circle depending on the speed of removal of stock is considered as promising. In this case, restrictions are set on the speed of removal of allowance and the level of vibration, which must be controlled during processing [2]. To do this, according to the current allowance in the AK microprocessor device, the allowance removal rate is calculated, and the vibration level of DS is measured by the built-in sensor. The control algorithm provides for the introduction of restrictions on the level of vibration and the speed of stock removal, which are determined experimentally for each type of ring in a comparative analysis with the results of the vortex control.

Improving the accuracy of processing the raceway of the outer rings of a ball radial double row bearing 256907 on SIW-4 internal grinding machines equipped with an AK microprocessor device, the allowance removal rate is calculated, and the vibration level of DS is measured by the built-in sensor. The control algorithm provides for the introduction of restrictions on the level of vibration and the speed of stock removal, which are determined experimentally for each type of ring in a comparative analysis with the results of the vortex control.

Improving the accuracy of processing the raceway of the outer rings of a ball radial double row bearing 256907 on SIW-4 internal grinding machines equipped with an AK microprocessor device, the allowance removal rate is calculated, and the vibration level of DS is measured by the built-in sensor. The control algorithm provides for the introduction of restrictions on the level of vibration and the speed of stock removal, which are determined experimentally for each type of ring in a comparative analysis with the results of the vortex control.

The results of multi-parameter ring quality control are accumulated in MSTP, which contributes not only to improving the quality of bearing ring processing, but also to obtaining and accumulating information about the dynamic quality of each machine individually, which is necessary to make a decision on adjusting TP in case of its alignment.

Thus, the results presented were the basis for the development of a monitoring method for the grinding process in the framework of PQM system and contributed to the implementation of a set of organizational and technical measures that virtually eliminated defects on the rolling surfaces of the bearing rings and, accordingly, significantly increased the operational reliability of the bearings.

References
[1] Push A V 2000 Modeling and monitoring of machine tools and machine systems STIN 9 12-20
[2] Ignatiev A A, Gorbunov V V and Ignatiev S A 2009 Process monitoring as an element of a product quality management system Saratov: SSTU 160
[3] Samoilova E M and Ignatiev A A 2018 Methods and algorithms for the intellectualization of monitoring technological systems based on automated machine tools integrated production. Saratov: SSTU 2 100
[4] Lin Z H and Hodgson D C 1988 In-process measurement and assessment of dynamic characteristics of machine tool structures Int. J. Mach. Tools Manufact 28 (2) 93-101
[5] Arshansky M M and Scherbakov V P 1989 Vibrodiagnostics and precision control on metal cutting machines (Moscow: Engineering) p 136
[6] Ignatiev A A, Karakozova V A and Ignatiev S A 2013 Stochastic methods of identification in the dynamics of machine tools (Saratov: SSTU) p 124

[7] Ignatiev A A, Karakozova V A and Ignatiev S A 2015 Transfer Function and Margin of Stability in the Dynamic System of a Grinding Machine Russian Engineering Research 35(2) 123-5

[8] Mikhelkevich V N 1975 Automatic grinding control (Moscow: Engineering) p 304

[9] Ignatiev A A, Samoilova E M, Shamsadova I S 2017 Assessment of the dynamic quality of machine tools using the autocorrelation functions of vibroacoustic vibrations News of Universities Volga region Technical science 2(42) 90-8

[10] Ignatiev A A, Shumarova O S and Ignatiev S A 2017 Recognition of defects in rolling surfaces of bearing rings during automated eddy current testing using wavelet transforms (Saratov: SSTU) p 108