The Structure of Automated Control Systems for Precision Machining of Parts Bearing

Ivanna Trokhymchuk, Kostiantyn Svirzhevskyi, Anatolii Tkachuk(✉), Oleg Zabolotnyi, and Valentyn Zablotskyi

Lutsk National Technical University, 75, Lvivska Street, Lutsk 43018, Ukraine
a.tkachuk@lntu.edu.ua

Abstract. One of the ways to improve the quality of bearing parts is the introduction of automatic control systems to improve the technological reliability of machines and increase the accuracy of machining of roller bearing rings. A significant advantage of these systems is that it is possible to compensate for technological factors by cheaper means compared to such as increasing the rigidity of the technological system, processing in modes with lower productivity, processing using more passes, using manual methods to compensate for wear of cutting tools, maintaining the required rigidity of the machine and the accuracy of its elements through periodic repairs. These methods are associated with either a loss of cyclical productivity or a significant loss of unproductive nature. Therefore, the errors of automated control systems should be considered as processing errors or as a scattering field of the dimensions of parts manufactured on a machine equipped with an automatic control system for precision machining. The share of error of the most automated control system in the total balance of the total size error is quite small and does not exceed 10…20%. The task of improving the accuracy and ensuring stability in technological systems is complex, so it is solved only by a comprehensive method by improving the accuracy of all elements of the technological system. Thus, automated control systems for precision machining of bearing parts is one of the main subsystems of flexible automated production in the concept of Industry 4.0.

Keywords: Accuracy · Active control · Machining process · Signal · Tolerance field

1 Introduction

To determine the expected accuracy of the automated technological system that controls the process of manufacturing bearing parts, it is advisable to consider the errors of the system that occur under normal operating conditions. Under normal conditions is understood as a set of physicochemical parameters of the system, in which the influence of external factors on the system is minimal. The measurement limits of each of the parameters that characterize normal operating conditions are the main characteristic. Failure to comply with these conditions causes additional errors that can reduce the accuracy and reliability of the system and distort the quality characteristics. The criterion

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for the accuracy of the automatic technological system is the total processing error. But during research and calculations, there is a problem of identifying its components and their share in the complex error. The sources of element-by-element methodological errors caused by the imperfection of the measurement method may be non-compliance with the principles of construction of measurement schemes, ignoring shape errors, control without taking into account the temperature of the part, control without taking into account deformations. Deviation from the theoretical schemes that allow obtaining the highest accuracy, is dictated by the achievement of possible simplification of the technological system as a whole.

The possibility of reducing the influence of technological factors on the accuracy of processing is the inclusion in the technological system of the control unit [1]. But here it is necessary to consider that introduction of each new link in the system the machine tool - the tool - a detail - the device can become a source of additional failures. Thus, it is necessary, if possible, to avoid complex multi-circuit control systems, using single-circuit systems based on direct measurement methods, which allow comprehensive compensation of processing errors by technological methods [2].

2 Literature Review

The efficiency of flexible automated readjustment production largely depends on the specification of input parameters for the formation of control programs. The optimal number and informational weight of these parameters can be identified in the comparative analysis and implemented in the appointment of priority factors influencing dimensional accuracy [3]. Adjusting devices synthesized on the basis of optimal algorithms choose the value of the adjusting pulse, using all available information about the previous pulses and the size of the machined parts, which is especially important because in real conditions the process of offsetting the machine is random. If debugging level changes were a deterministic process, then debugging levels could be determined with any degree of accuracy [4]. In the process of processing products, along with the deterministic, often systematic linear, there is a random component, which determines the nature of the process. In such circumstances, the magnitude of the uniform systematic offset of the debugging per part may also vary from implementation to implementation. Thus, only a statistical assessment of the level of debugging of the machine on each cycle will ensure the effectiveness of controlling the accuracy of such processes.

Active size control systems are used in almost all bearing manufacturing operations. Such systems allow compensating both functional and accidental errors in the course of processing [5]. Thus, these systems have the greatest compensatory properties and, accordingly, correspond to the simplest mathematical models [6, 7]. The high-frequency component of technological errors is one of the most difficult to compensate, as it arises as a result of fluctuations in the values of allowances for processing. To reduce it, it is necessary to increase the accuracy of previous operations [8]. Therefore, active control systems are used in all grinding operations. In general, active control includes any method of control, the results of which are manually or automatically influenced by the technological process [9]. Active control can be considered as a system of "size control". The main factors that determine the scattering of the size of the parts are the dimensional wear of the cutting tool, thermal and force deformations of the technological system [10].

The geometric or static accuracy of the machine tool mainly determines the shape errors of the workpieces and has no significant effect on the scattering of dimensions [11]. The main meaning of using the method of active dimensional control is to eliminate the impact on the accuracy of machining wear of the cutting tool, thermal and force deformations of technological systems. Measurement errors are part of the total error of active control [12]. The share of static error of the devices in the total volume of the total processing error is quite insignificant, in some cases, the share of the error of the devices is only 2…4% of the total error of the control. The rest of the error is determined mainly by the influence of technological factors.

Grinding of holes and rolling tracks of roller bearing rings in the vast majority is performed according to the scheme of centerless grinding. The bearing ring with its base end is mounted on the surface of the cartridge with a magnetic grip, and the other base surface - the outer raceway rests on two supports, the working surface of which is made in the shape of the raceway. These supports are installed at a given angle to the center of the ring, and the center of the conditional circle, around the perimeter of which is the working surfaces, lies slightly above the geometric center of the ring. Thus, some eccentricity is created, due to which an additional force acts on the ring during grinding, forcing it to be constantly pressed to the support [13].

3 Researches Methodology

Geometric or static accuracy of the machine determines the shape errors of the workpieces and the scattering of dimensions does not significantly detect [1, 8]. The main use of the method of active control of the sizes consists in elimination of influence on accuracy of processing of wear of the cutting tool, thermal and force deformations of technological systems.

Measuring errors are part of the total error of active control, but the share of static error of instruments in the total amount of total processing error is quite small. The share of instrument error is only 2…4% of the total error. The remaining errors are determined by the influence of technological factors. Grinding of holes, and rolling tracks of roller bearing rings is performed according to the scheme of centerless grinding. In Fig. 1 shows a diagram of the centerless grinding of the hole of the inner ring of the roller bearing.

The bearing ring with its base end is mounted on the surface of the cartridge with a magnetic grip, and the other base surface - the outer raceway rests on two supports, the working surface of which is made in the shape of the raceway. The base supports are installed at a certain angle to the center of the ring, and the center of the conditional circle, around the perimeter of which are the working surfaces, lies slightly above the geometric center of the ring. Thus, an eccentricity is created, due to which a force acts on the ring during grinding, forcing it to be constantly pressed against the base supports.

During grinding, the ring is held by a magnetic chuck, resisting and rubbing the raceway on the surfaces of the base supports, and rotates at a frequency of 200…600 rpm. The direction of rotation - opposite to the direction of rotation of the grinding wheel.

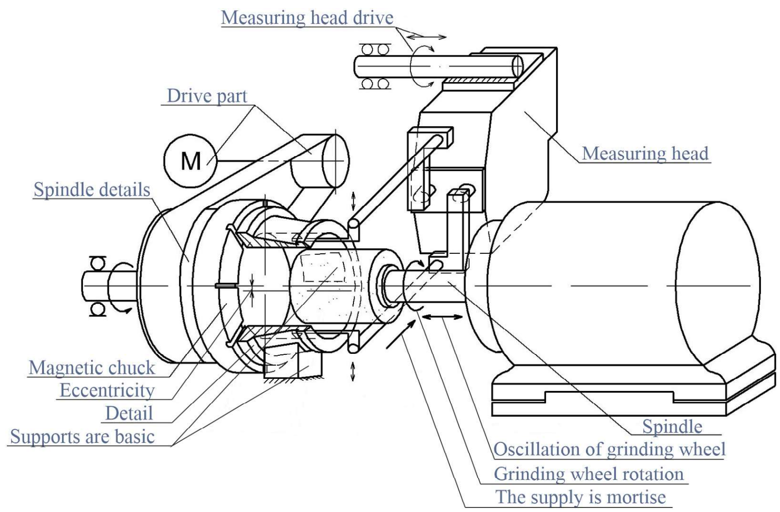

Fig. 1. Scheme of centerless grinding of the hole of the inner ring of the roller bearing

Cutting tool - the grinding wheel has an independent drive. For internal grinding machines, the spindle is a motor that provides a high speed with minimal vibration. The grinding wheel is mounted on a frame, which is installed in the spindle and provides rotational movement and rectilinear movement along the axis. In addition, the spindle can move at different speeds in the transverse direction.

A feature of the control system is that it is a single-acting device that includes both linear elements and elements with nonlinearities of the transmission characteristics [14]. Moreover, all elements are usually connected in series (Fig. 2).

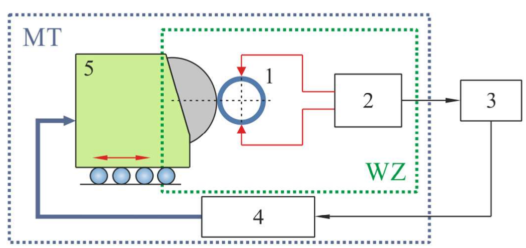

Fig. 2. Scheme of operational control: MT – machine tool; WZ – working area of machining part; 1 - workpiece; 2 - primary measuring transducer; 3 - control system; 4 - control unit; 5 - the executive body of the machine

The static accuracy of such control systems is affected by: wear of the contact tips, errors in the position of the measuring head relative to the controlled surface of the part, temperature and force deformations of the system, errors in the shape of the part.

The primary measuring transducer 1 is installed in the processing area of the part WZ and is used to convert the linear size of the part (in this case - the diameter) into an intermediate signal. The signal is processed by the control system 2, at the output of which control systems are formed. The control systems enter control unit 4 and are implemented by the executive bodies of machine tool 5, which, in turn, move the cutting tool. Errors in the shape of the part: deviations from roundness, cut, waviness, for the case of processing of cylindrical surfaces, affect not only the result of the process but also the accuracy of measurement for the case of static dimensional monitoring.

Let the initial size of the workpiece coincide with the line O_1O_1 (Fig. 3), and the size to be obtained and the size of the adjustment coincides with the line O_2O_2. Accordingly, the positions of the lines O_1O_1 and O_2O_2 determine the value of the allowance for processing ΔD. The head of the automatic control means measures the detail x_i at some point in time t_i. This size due to the presence of shape errors in the measurement plane is not constant and in the first approximation will be characterized by a variable, for example, a sinusoidal signal with amplitude A_i and period T_0, moreover

$$A_i = (x_{i\,\max} - x_{i\,\min})/2 \tag{1}$$

$$x_{i\;av} = (x_{i\,\max} + x_{i\,\min})/2 \tag{2}$$

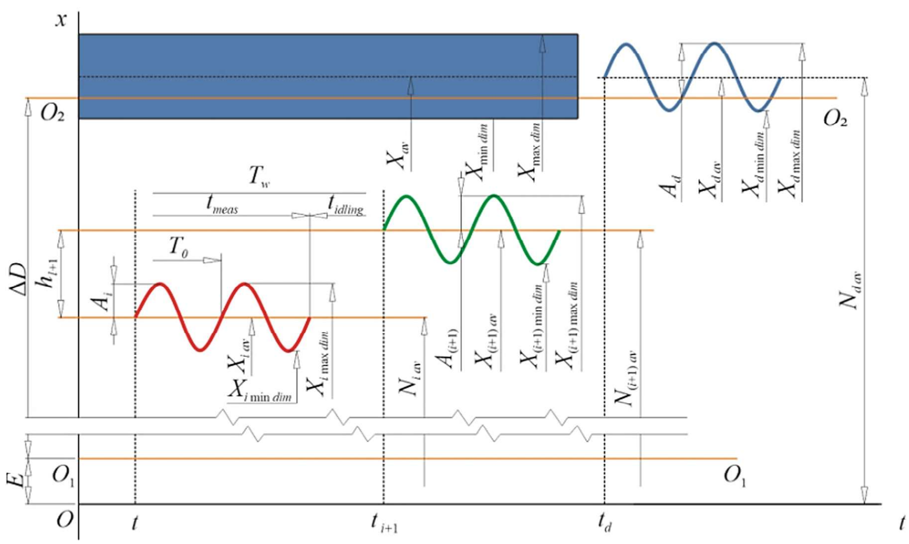

Fig. 3. Graph of resizing during discrete monitoring

The period T_0 is determined by the type of shape errors and the speed of movement of the part in the measurement plane. Thus, if the control of the diameter of a cylindrical part having a speed n is carried out by a two-point diametric measuring device, and the main error of the shape is manifested as an oval, then $T_0 = n/2$. For workpieces with a cut in which the number of faces is equal to z, the period is equal to $T_0 = n/z$.

The measurement time t_{meas} is different for different types of devices. For devices with gauge plugs that provide surface contact with the product, the control time t_{meas} is determined by the value of the longitudinal feed of the tool, the number of double strokes per minute the period T_{lf}, and in the extreme case may be equal to this period $t_{meas} \leq T_{lf}$. In practice, more often there is some idle time t_{idling}.

When inspecting internal surfaces (holes) with a caliper, the size will be fixed, without taking into account the deformations of the product and caliber, as its smallest size is acceptable, and, accordingly, the line of adjustment, or the size of the caliper, should deviate from the smallest limit. The size of the $h_{\min}$ of the detail tolerance field by the value of h_d. Then the tolerance field $T_x = h_{max} - h_{min}$ must be at least:

$$T_x = 2A_d + h_d \tag{3}$$

where A_d - the amplitude of the error at the end of processing; h_d - change in size between two measurement cycles at the end of processing, equal to twice the thickness of the layer removed in one double stroke.

Without taking into account the dynamic errors, in the case of operation in quasi-static mode, the device that has a point periodic contact with the surface of the hole will fix as acceptable the largest size of the product $h_{i\,\max}$, and the debug line should deviate from the largest size by h_d. In this case, the tolerance field is determined from condition (3).

The measurement time t_{meas} in such devices must be such that during the control period all points of the controlled product have passed through the measuring tips, it is necessary to comply with the condition $t_{meas} > 60/n$, where n is the workpiece speed per minute. Before starting the measurement, the probes of the measuring tips must be diluted to a value E that exceeds the allowance ΔD. But it should be noted that the stroke of the $H_{i\,\max}$ probes will increase until it reaches the value of $N_{d\,work}$. The cycling work of the measuring elements is defined as

$$T_{pp} = t_{meas} + 2H_{i\;max}/v_{av} + t_{idling} \tag{4}$$

where $N_{d\;work} = \Delta D + E$ - the course of the probes during the calibration at the end of the processing; v_{av} - the average speed of calibration (supply) of probes.

In some cases, the measuring head, in order to reduce the wear of the tips, rotates together with the part, thereby controlling any size in the range from $h_{i\,\min}$ to $h_{i\,\max}$. But this method reduces the accuracy of control, as the tolerance, in this case, will be:

$$T_x \geq 4A_d + h_d \tag{5}$$

Devices that measure one random size reduce the accuracy of processing in general. The change of the size during continuous control taking into account errors of the form is shown in Fig. 4.

The line of adjustment coincides with the line O_2O_2, and the line O_1O_1 characterizes the allowance B; removal of the allowance takes place along the SS line, it can be performed not at a constant speed; at the beginning of the measurement process, this speed is characterized by the angle α_D, and at the end of the processing cycle - the angle α_d.

In the presence of shape errors, the measuring system will issue a variable, in the first approximation, close to a sinusoidal signal with a variable amplitude A_i, but with a constant period T_0. This period depends on the frequency of rotation of the part and the type of shape errors.

The size obtained as a result of processing can be determined

$$x = x_H - \Delta D + F(t) + f(t) \tag{6}$$

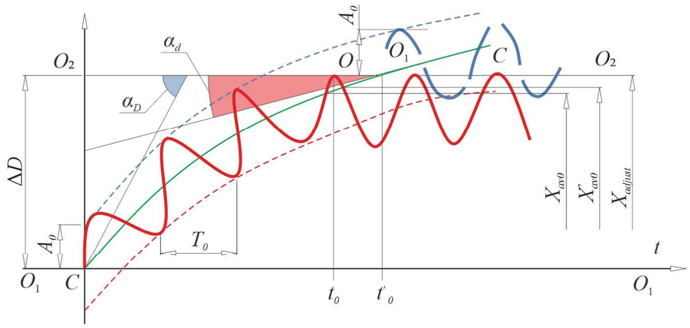

Fig. 4. Graph of resizing during continuous monitoring

where x_H - the size that determines the level of adjustment of the machine tool; $F(t)$ - a non-random function of time, or a mathematical expectation that describes the line CC, for example, using the least-squares method; $f(t)$ - a centered random function of time.

For slow processes, ie for quasi-static modes, the actuation of the system will occur at the first crossing of the line by the line size of the debugging level of O_2O_2, after which the supply will be turned off, and the average size of the details will remain unchanged (solid sinusoidal line). But the actuation of the actuator, which stops the supply at time t_0 (at point O), may not occur. Then the operation will occur at time $t_0^{'}$ of the next intersection of a line of variable size with the level of O_2O_2 (point $O_1^{'}$). But the average size $x_{av\,0}^{'}$ of the detail (dashed sinusoidal line) at this point will be different from $x_{av\,0}$. The difference $x_{av\,0}^{'} - x_{av\,0}$ will depend not only on the amplitude of the error of the shape of A_d at the end of the processing cycle but also on the cutting speed at this time and on the size of the angle α_d.

Based on the graph-analytical method, it can be determined that the difference in the sizes $x_{av\,0}^{'} - x_{av\,0}$ can be approximately $A_d/2$ and exceed this value. Size scattering range for a similar class of control systems

$$T_x \geq (5/2)A_d \tag{7}$$

For small feeds at the end of the processing cycle, the tolerance value may be $T_x \approx 2A_d$.

Devices for active control of parts during machining provide information about the current size of the part in one cross-section. In the presence of shape errors and uncertainty or instability of these errors in both magnitude and geometric shape, the dimensions of individual sections of parts may exceed the tolerance field.

In practical cases, the tolerance of the shape error is not indicated in the drawing, it can take any value and type within the tolerance field for the size (Fig. 5).

If the control section is the average value of the section I-I along the length of the part, and the active control device is set in the middle of the tolerance field, then changing the shape error from concavity (contour 1) to convexity (contour 2) can lead to the size of extreme sections tolerance T, respectively, in plus or minus. Therefore, the scattering of the dimensions of these sections can be $2T$, even with the absolutely accurate issuance of the final command to stop processing. The location of the controlled section in position II-II eliminates the effect of convexity and concavity of the part, but in this case, the danger is the manifestation of direct (contour 3) or reverse (contour 4) taper.

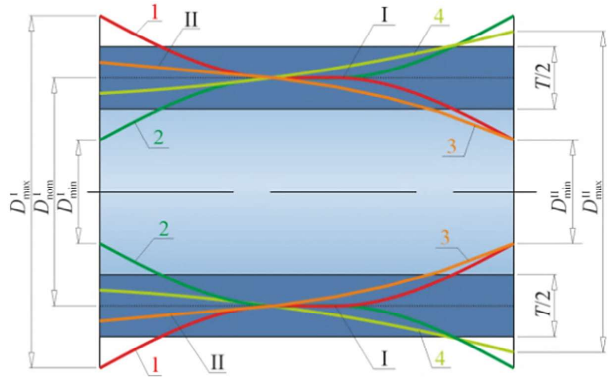

Fig. 5. Typical errors in the shape of cylindrical parts

Dynamic errors of the active control system are determined from the analysis of a typical structural scheme (Fig. 6). In the scheme (Fig. 6), the input signal is the size of the surface to be treated $x_{input}(t)$. The signal from the processing zone arrives with some delay, which is determined by the constant τ_1, in the control zone. The signal is received by a transducer, which is an oscillating or aperiodic link with a second-order transfer function and is transmitted through an amplifier with a gain of k_2 to the trigger and its relay with a time delay constant τ_2.

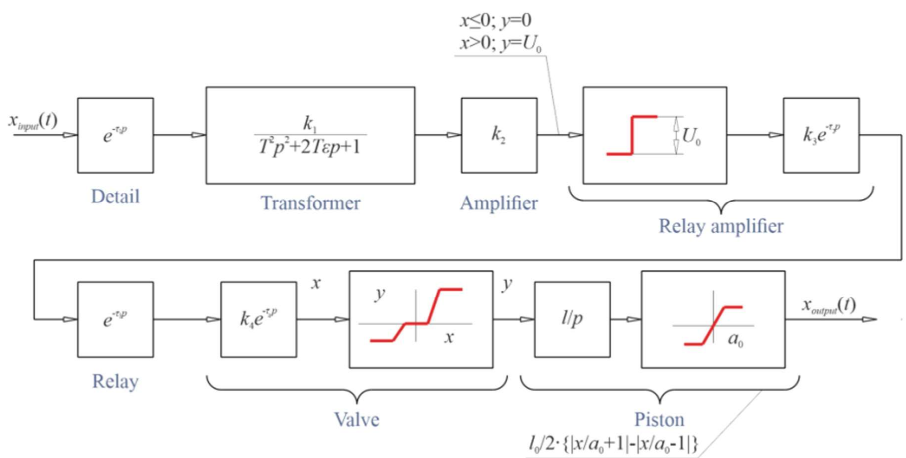

Fig. 6. Block diagram of the active control system

Next, the signal is fed to the actuator relay with a time constant of the machine tool and the actuator of the machine tool.

4 Results

Increased requirements for dimensional accuracy and quality of processing surfaces at the final stage of grinding can be realized by means of adaptive systems of formation of control commands (Fig. 7).

In such systems, the end of machining with a given final rate of removal of the allowance is provided regardless of such variables as the amount of allowance for processing, the feed rate, the cutting properties of the grinding wheel.

In circuits using adaptive devices, the operation of the command to enable the final stage of processing is determined by the current rate of removal of the allowance. There is a linear relationship between the rate of removal of the allowance v_p and the value of the allowance for finishing ΔD_v:

$$\Delta D_v = T_r(v_v - v_k) \tag{8}$$

where v_v - the rate of removal of the allowance at the beginning of finishing; v_k - the rate of removal of the allowance at the end of the processing; $T_r = \mathrm{tg}\alpha$ - cutting constant for the machine tool.

To ensure a constant final rate of removal of the allowance v_k, each initial value of the initial speed v_v must correspond to a certain value of the allowance for the final processing ΔD_v. To fulfill this condition, it is necessary that the command for final processing is given when

$$\Delta D_v + \Delta D_{sv\,0} - T_r v_v = 0 \tag{9}$$

where $\Delta D_{set\,0}$ - set during debugging the value of the allowance, at which $v_p = 0$.

Turning to the values of the allowance for processing ΔD and the removal he rates v_p, we obtained two states of the system:

1) the mode of grinding processing with giving

$$\Delta D_v + \Delta D_{sv\,0} - T_r v_p > 0 \tag{10}$$

2) the feed is switched off and grinding goes into the process of fine grinding

$$\Delta D_v + \Delta D_{sv\,0} - T_r v_p \le 0 \tag{11}$$

In the scheme (Fig. 7), the workpiece is controlled by the measuring head 1.

The signal from the measuring transducer is converted in measuring circuit 2 and amplified by unit 3. The electrical signal from the amplifier 3, in magnitude proportional to the current allowance $U_{\Delta D}$, is transmitted to the reading device 4 and the input of the command driver 7. The operation of the shaper takes place when comparing the signal $U_{\Delta D}$ with the signal U_{set} coming from the control device 9. In the case of $U_{\Delta D} \le U_{set}$, the shaper is in the off state, if $U_{\Delta D} > U_{set}$ - the command relay is turned on and the control signal is fed to the circuit of the machine tool 12. A converter 6 is connected to the output of the amplifier 3, which differentiates the signal $U_{\Delta D}$, and the signal $dU_{\Delta D}/dt$, which is transmitted to the amplifier 5, will be proportional to the current rate of removal of the allowance. At the output of the amplifier 5, with a gain of k_3, the polarity of the signal changes and is equal to $-k_3(dU_{\Delta D}/dt)$. This signal is fed to the shaper of the command 10.

The same input is supplied with voltage U_{set0} from the setter of the static level 8, the other input of the shaper 10 is fed a signal from the output of the amplifier 3 $U_{\Delta D}$. The

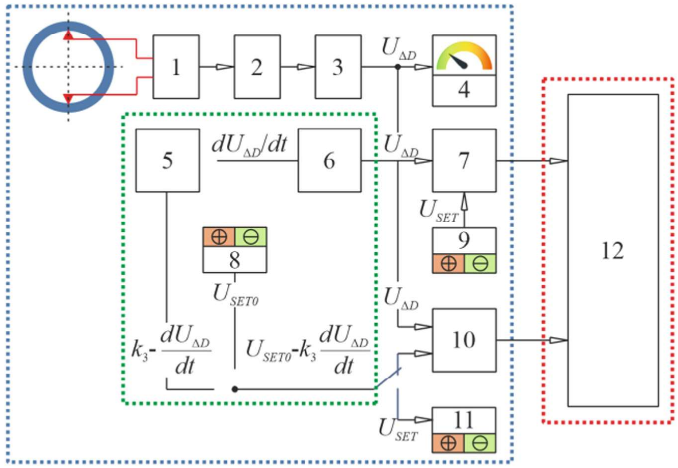

Fig. 7. Scheme of the device with an adaptive command system: 1 - measuring head; 2 - signal converter; 3, 5 - amplifiers; 4 - reading device; 6 - signal differentiation device; 7, 10 - command generation devices; 8 - setter of static level of operation; 9, 11 - task commanders; 12 - control scheme of the machine tool

signals coming to the input of the shaper 10 correspond to the linear values included in Eqs. (10) and (11).

The proposed scheme will provide closed feedback on the rate of removal of the allowance in the final stage of grinding using the feed tracking mode.

5 Conclusions

The problem of ensuring the accuracy of parts, the manufacturing cycle of which includes the grinding operation is complex and in automated production should be addressed at the levels of the configuration of the technological system, during design and technological preparation of production and by optimizing the sequence of processes and processing modes.

To ensure the accuracy of the product, it is necessary to follow the principles and methods that provide consistent continuous monitoring of dimensional and other interrelated geometric parameters of the surfaces of parts, but the defining stage of the result is the final grinding operations. The efficiency of automated production depends on the specification of input parameters for the formation of control programs. The optimal number and informational weight of these parameters can be identified in the comparative analysis and implemented in the appointment of priority factors influencing dimensional accuracy.

The introduction of automated control and process control improves quality indicators, but at the same time requires additional costs that affect the cost of production. Automated production requires a consistent process approach, especially at the stage of its preparation, in order to build a technological process that would guarantee the necessary quality indicators, and its economic evaluation is carried out both at the beginning of a comprehensive analysis of the technological system and after.

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