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SOLID MECHANICS

IMPROVING THE ACCURACY OF SURFACE WEAR MEASUREMENTS OF MACHINES PARTS

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ABSTRACT: The article considers the method of increasing the accuracy and speed of measurement of wear and deformation of parts by modern information-measuring complexes. The method helps to solve the problem of simultaneous provision of two contradictory requirements - high accuracy and sufficient speed of measurements. The authors propose a variant of the switched structure of the controller of the tracking system and perform mathematical modeling of its operation. The advantage of the proposed structure of the controller is to ensure high-quality operation in several modes: software movement of the measuring element at high speeds with minimal deviation from the specified trajectory, rigid positioning with step control without over-regulation, high sensitivity at small movements in the measurement area.The results of the study can be used in the development of precision automated drives for automated measuring systems of high accuracy and performance.

KEY WORDS: automated drives, geometric parameters, information and measuring systems, regulator structure, surface wear.

1 INTRODUCTION

The wear of parts during the operation of machines causes a change in the size of the working surfaces. To understand the physical process is hard and may not be possible in complex systems These changes occur unevenly and distort the original geometric shape of the surfaces of the parts,stock basing, finite element analysis, terra in modeling, and numerical approximation. Changing the dimensions and geometric shapes of the working surfaces of parts leads to the need to stop the machine for repairs. Computerized control systems for geometric characteristics detect deviations from a given geometric shape, quantitatively and qualitatively evaluate these changes [1–4]. Automated drives provide high-quality operation of computer systems for monitoring

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geometric characteristics in several modes. Besides, such models must continually adapt to operational changes based on data collected directly from the physical objects [5–7]. The main modes are as follows: software movement of the measuring element at high speeds with minimal deviation from the specified trajectory, rigid positioning with step control without over-regulation, high sensitivity at small movements in the measuring area. Most modes consider, to a lesser extent, the stage characteristic of the measurement process, which cause short comings for timeliness and which cannot accurately respond or judge to abnormal measuring conditions immediately.

In addition, the effective measurement parameters or features of the part have to be discussed and analyzed prior to model construction. The variety of data corresponding to the measurement parameters have to be considered in collection process of the data. This results in the effectiveness and performance of the estimation part wear model [8–14].

Therefore, the problem of developing a new controller structure with improved indicators of dynamic accuracy of automated drive to ease the operating mode of the central computer and to realize a dialogue mode of information exchange between the embedded microprocessors of blocks and raises the operating efficiency is relevant and needs to be solved [15, 16]. The aim of the study is to simultaneously ensure two conflicting requirements - high accuracy and sufficient speed of measurements.

2 Background of Research

The construction of digital models is a key component of surface control. However, to obtain all the benefits of the computer processing of measurement information and of the measuring sensor management enhancement, it is required to have a holistic view of the system and its interconnectivity [8]. When measuring surface wear in a real-time state, it should be taken into account that the accuracy and reliability of the results based on signal data are affected by the amount of data processed in a single time frame [10]. Increasing the speed of the touch probe can significantly improve the efficiency of measuring operations. It is possible to ensure the necessary dynamic accuracy of the sensor under the conditions of increasing the measurement speed by improving the structure of the regulator. This approach has been widely used also in process improvement automation of parts machining and even elimination of parts errors in the production process [13].

As the initial variant of the regulator, the PI-regulator of a typical tracking system with a transfer function is accepted [12].

$$K(\omega) = \frac{K_0}{j\omega_0}\left(1 + \frac{1}{j\omega_1 T_1}\right)\left(\frac{1}{1 + j\omega_2 T_2}\right), \tag{1}$$

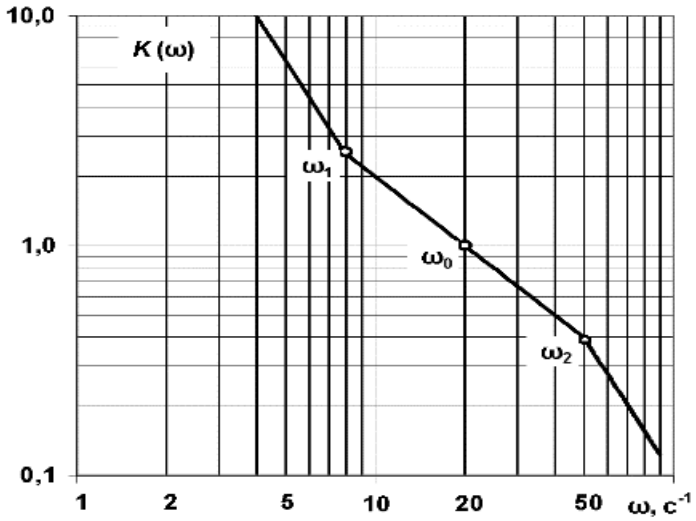


Fig. 1: Logarithmic amplitude-frequency characteristic of an open system.

where ω is the cyclic frequency; K_0 is the coefficient that determines the cutoff frequency ω_0 of a closed system; T_1 is a time constant that determines the lower connected frequency ω_1; T_2 is the time constant of the periodic link, which determines the upper connected frequency ω_2.

The logarithmic amplitude-frequency characteristic (LAFH) of an open tracking system with second-order statism is shown in Fig. 1.

Limitations on the way to improve the dynamic properties of the tracking system by increasing the frequencies ω_0 and ω_1 due to the increase in the oscillations of the drive and the increase in over-regulation in transient modes.

To solve the problem, a differential link is introduced into the controller, which generates a signal of the rate of change of deviation. Then, the distance is calculated between measuring points and theoretical points, the location is obtained by developing the mirror method. The optimal matching parameters of the theoretical points are determined by the mirror point cloud. The time constant of the differentiator is chosen equal to the time constant of the closed system T_0, determined by the bandwidth limit ω_0. With the desired exponential nature of the input effect U_{inp1}, the laws of change of the deviation signal $\Delta U(t)$ and its velocity $\Delta \dot{U}_d(t)$ determined by the differentiator with a time constant $T_0 = 1/\omega_0$ has the form [12–14]

$$\begin{aligned} &\Delta U(t) = U_{\text{inp1}} e^{-\frac{t}{T_0}}, \\ &\Delta \dot{U}_d(t) = T_0 \frac{\partial}{\partial t}\left(U_{\text{inp1}} e^{-\frac{t}{T_0}}\right) = -U_{\text{inp1}} e^{-\frac{t}{T_0}} = -\Delta U(t), \end{aligned} \tag{2}$$

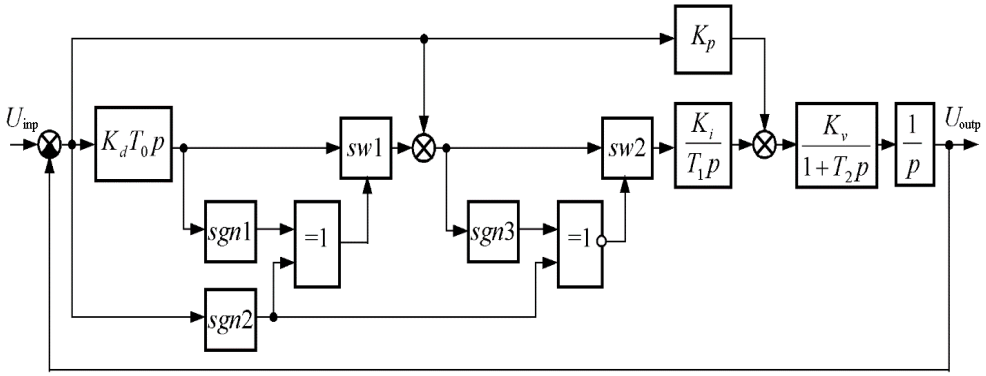


Fig. 2: Block diagram of the tracking system with the proposed regulator.

where t is the time that has elapsed since the input action was submitted.

From Eq. 2 we have $\Delta U(t) + \Delta \dot{U}_d(t) = 0$ the signals of deviation and the rate of its change during the exponential development of the step action are the same in absolute value and have opposite signs. This ratio is the basis of the idea of synthesis of the proposed regulator, the structure of which is shown in Fig. 2.

Determinants of the sign of deviation signals and their speed are introduced into the structure of the regulator. The logical element "= 1" (exclusive or) set at their output forms the key opening command "*sw*1" only when the signs of the deviation signals and its derivative are opposite, i.e. during periods of decreasing deviation in absolute value. The signal generated at the output of the key "*sw*1" is fed to the second adder together with the initial deviation signal.

If the deviation decreases more slowly than the time constant T_0, the signal at the output of this adder will not differ from the sign of the deviation to the sign of the deviation. Then the second logical element will issue a command to open the key "*sw*2", connecting the integrator input to the adder, and it's derivative. At an excessive rate of deviation, the signs of the signals at the input of the second logic element become different and the key "*sw*2" is closed, suspending the integrator.

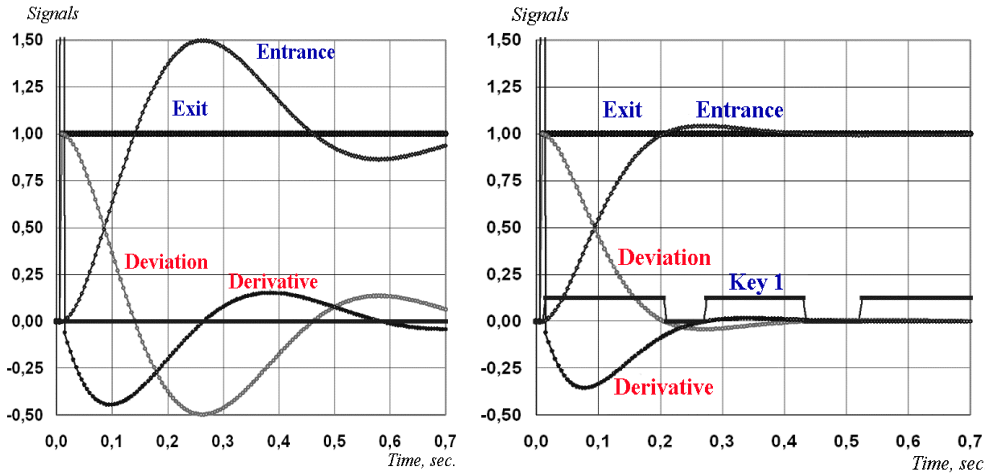
The key "*sw*2" opens again after changing the sign of the deviation, i.e. with the beginning of its growth. With increasing deviation, the key "*sw*1" is always closed, and the key "*sw*2" is open because the second logic element "= 1" in this case works with the same input signals.

During this period, only the proportional component of the deviation is fed to the integrator and the structure of the regulator is no different from the usual one. The summed proportional and integral components of the signal are then fed to the speed circuit of the drive.

The proposed version of the regulator allows a greater convergence of the characteristic points ω_1 and ω_2, until their complete coincidence when the normal system goes into self-oscillating mode. The proposed option remains stable in this case, providing even higher performance and high-quality transients, which is confirmed by the results of comparative computer simulations for different laws of input influence, presented in the form of diagrams. This control approach has better time-varying characteristics and is more sensitive in distinguishing abnormal states compared with the traditional approach. Further, in order to better evaluate the state of the system, the multi-level control limits were considered in the proposed approach by separation the identified input and output signals to better meet the actual needs [10].

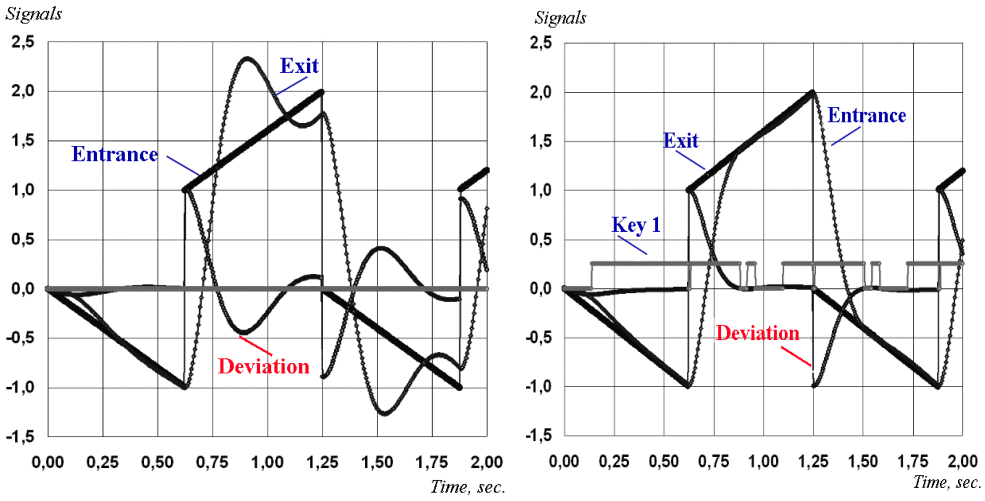
The most telling, though not always objective, is the system's response to a single jump of input. The reasons for the above behavior of the conventional system (Fig. 3(a)) are quite natural at the selected ratio of the connected frequencies of the LAFH. There is a high fluctuation, which leads to significant over-regulation and delay of the transition process. In the proposed variant, due to the operation of the regulator by the above algorithm, it is possible to repeatedly reduce over-regulation and reduce the transient time (Fig. 3(b)).

In addition to the input and output signals, the diagrams show the deviation and its derivative signals, as well as the periods of switching the differential link: high level of the command "Key 1" corresponds to the interval of connection of this link to the integrator input, low - return to a normal structure.



(a) (b)

Fig. 3: Jump-like transients of typical (a) and proposed (b) tracking systems.



(a) (b)

Fig. 4: Combined transients of conventional (a) and proposed (b) systems.

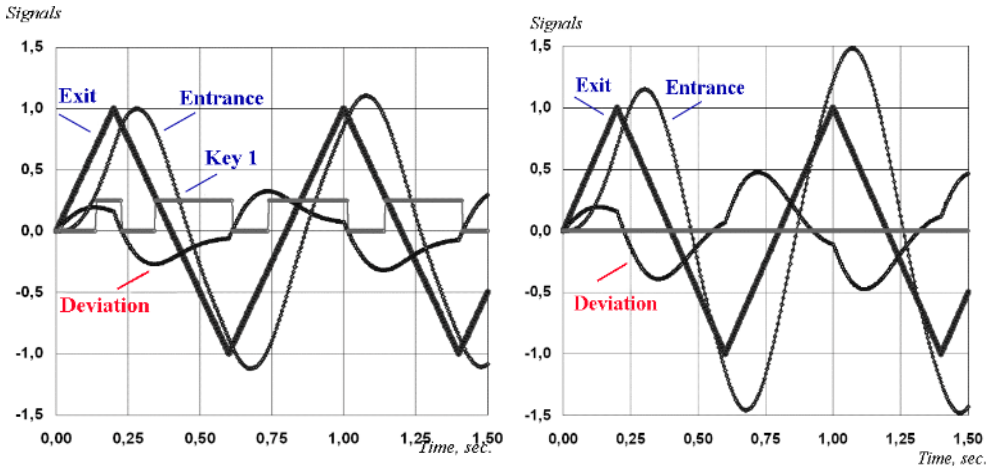
It is more objective to compare the reaction of the two systems to the combined input effect, which is to switch to non-zero speed (Fig. 4).

The conventional system (Fig. 4(a)) retains the same shortcomings as in the rectangular action, and the proposed demonstrates high “toughness” and rapid ”binding” to the input signal with the transition to zero deviation in the linear area of influence (Fig. 4(b)). The advantages of the proposed system are obvious with the input action, which is not accompanied by jumps – with a triangular signal (Fig. 5).

The main harmonic component of this signal is close to the bandwidth of the system ω_0, so this effect should be attributed to the extremely fast and difficult to test. The collected data are often random in actual engineering applications, and their probability density is also in an unknown state, for this the specific distribution form cannot be determined. However, the proposed option (Fig. 5(b)) shows significantly fewer fluctuations compared to the conventional system (Fig. 5(a)) and works with almost half the error.

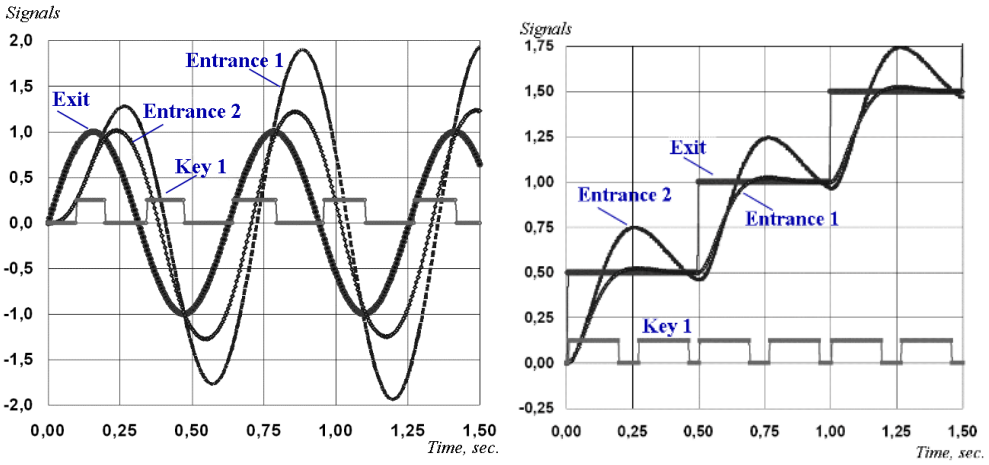
For comparison, the reaction of both systems is shown in one diagram. The signal “*Output* 1” describes the behavior of a conventional system, “*Output* 2” describes the behavior of the proposed system. In the proposed system there is a fairly high degree of suppression of resonant phenomena in contrast to the usual, in which there is a significant increase in the amplitude of the output oscillations.

The most striking advantages of the proposed system are manifested in the development of a series of successive positioning, for example, with multiple stepped effects (Fig. 6(b)).



(a) (b)

Fig. 5: Operation of conventional (a) and proposed (b) systems under triangular exposure.



(a) (b)

Fig. 6: Operation of systems under sinusoidal (a) and stepped (b) influences.

The proposed variant of the switched structure of the controller of the tracking system and the results of the mathematical study of its operation can be used in the development of precision automated drives of automated measuring systems of high accuracy and performance, as well as in other automatic control systems, where obtaining the best accuracy.

3 Ordinal Approach

Let us analyze the data and determine the optimal ratios and absolute values of the characteristic parameters of each of the structures, which we will call optimal. Consider the results for the basic structure. This will provide an increased level of reliability of measurements at all stages of the of machines parts life cycle with a comprehensive change of diagnostic parameters in the event of a malfunction [9, 17]. In the case of step effect, the value of over-regulation (Fig. 7) has a pronounced minimum when changing the cutoff frequency for a fairly wide range of values of the lower connected frequency as a parameter from almost 63 to 250 rad/sec, in which minimal over-regulation takes place at the same value $= 250$ rad/s.

The value of over-regulation as a function of the marked zone varies from 17% to 51.5%, without having an extremum. Another important indicator is the duration of the transient process (Fig. 8), in the same zone with a fixed cutoff frequency, has a certain minimum of 24 ms at the value of the lower connected frequency $\omega_1 = 125$ rad/sec. Thus, the set of two main indicators that characterize the accuracy and speed of the system, pre-set the zone of optimal adjustment of the controller on the basic structure. It is necessary to be convinced, how much other indicators meet requirements of sufficient quality. The same analysis of the results will be performed for the proposed structure, considering the data in the form of diagrams in the same coordinates.

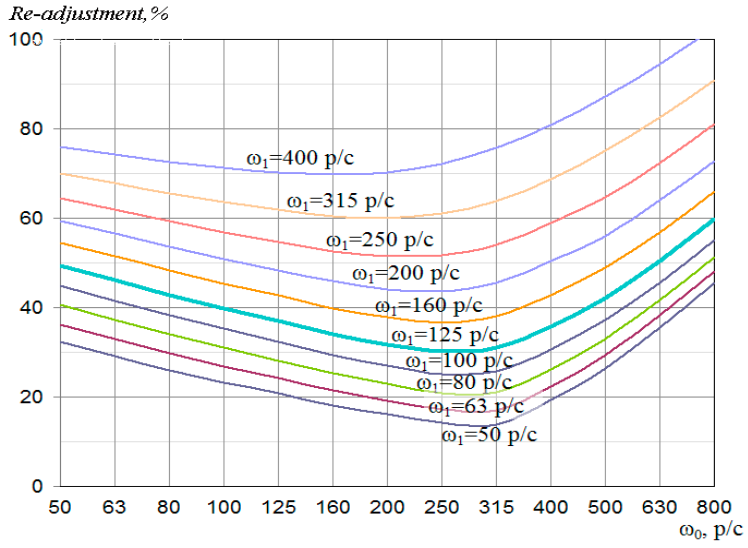


Fig. 7: Dependence of the readjustment indicator on the parameters ω_0 and ω_1.

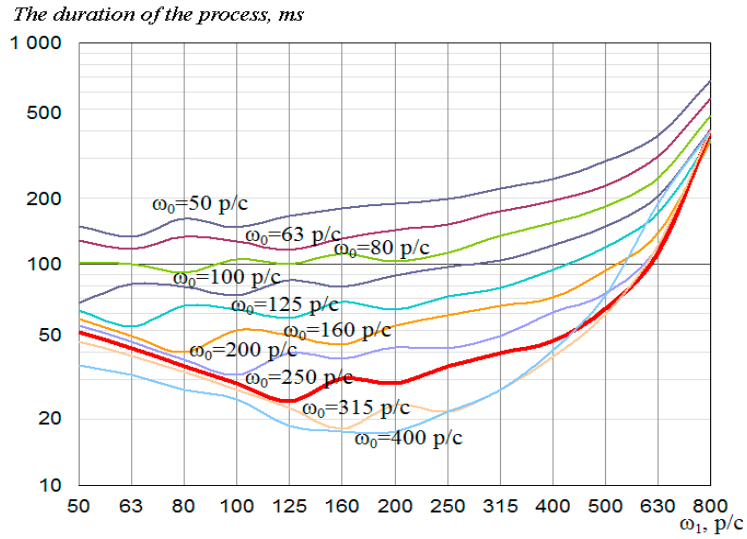


Fig. 8: Dependence of the duration of the transition process.

Figure 9 shows that due to the new method there is a range of values of the cutoff frequency $\omega_0 < 200$ rad/sec, in which over-regulation is absent for any value of the lower connected frequency ω_1, ie this indicator cannot serve as a criterion for

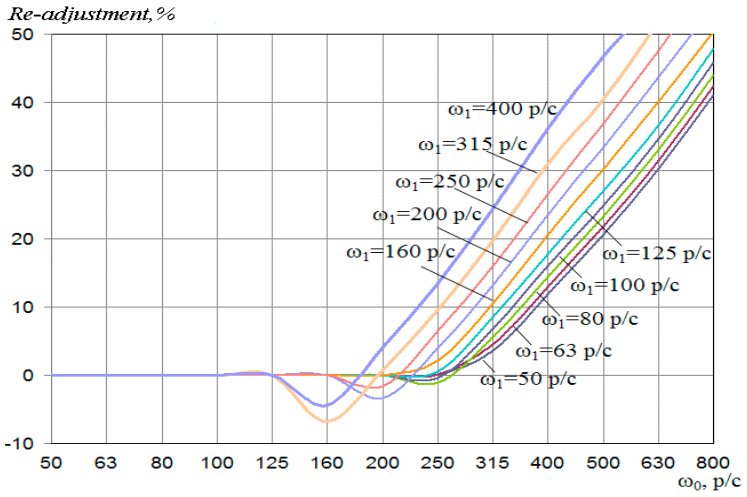


Fig. 9: Dependence of the over-regulation indicator on the parameters ω_0 and ω_1 for the regulator of the proposed structure.

selecting the optimal value ω_1 and imposes certain restrictions only on the range of permissible values of frequency ω_0.

A negative value of the fixed value of the over-regulation indicates the appearance of an extremum in the transient characteristic before the end of the actuator in the final position, i.e there is excessive damping of oscillations.

Analysis of the second indicator – the duration of the transition process (Fig. 10) allows to make the final choice of the desired parameters of the regulator. The duration of the transient process is smaller, the higher the cutoff frequency ω_0. But the latter already has a limit at the top at 200 rad/sec and therefore should choose this value.

As for the choice of frequency ω_1, the considered two criteria do not give an unambiguous answer. Therefore, it is necessary to resort to consideration of other indicators of an estimation of the quality of work of the system. Among them, the root means square and the mean value of the modulus of error of the trajectory relative to a given curve of the circumference of the surface are important.

Analysis of these indicators for both periodic signals of different shapes and irregular with different laws of normalization and filtering, confirms that under all equal conditions in the proposed structural solution should choose the maximum possible value of the lower connected frequency, thus achieving the lowest level ω_1 of a dynamic error. Therefore, given the curve with the parameter $=$ 200 rad/sec in the diagram of Fig. 10, it can be concluded that the optimal frequency value for the considered structure is 400 rad/sec.

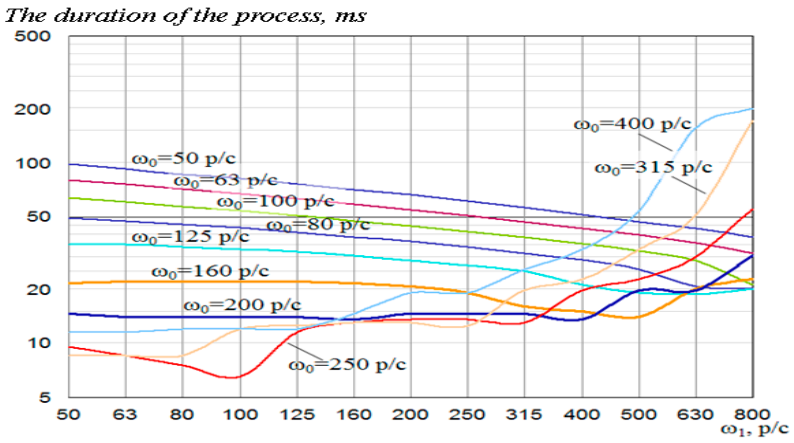


Fig. 10: Dependence of the duration of the transient process on the parameters and for the regulator of the proposed structure.

Not worse indicators can be received at a choice of parameters of the regulator $\omega_0 = 160$ rad/sec and $\omega_1 = 500$ rad/sec (Fig. 10) that is confirmed by results of computer modeling. But it testifies more than the offered structures have the expanded areas of admissible values of parameters in comparison with the basic variant at which high indicators of work of monitoring system remain. Therefore, the parameters of the optimal setting of the controller should be clarified for the proposed structure according to option 7.

4 Illustrative Examples

Table 1 presents the main final data, and the diagram of Fig. 11 – logarithmic amplitude-frequency characteristics of the studied structures in the tuned state. The characteristic of the improved structure is shown for two extreme cases: the main curve that intersects the horizontal axis with the value $|K(\omega)| = 1$ (0 dB) at point ω_{v0}, which corresponds to the case of locking the differential link, and the additional curve, which intersects the same axis at point ω_{v1}, which corresponds to switching intervals of this link with the maximum coefficient determined by Eq. (1).

Table 1: Final adjustment data of regulators

Parameter	Basic structure	Proposed structure			
		Variant 7, a		Variant 7, b	
		$k_d = 0$	$k_d = 1$	$k_d = 0$	$k_d = 1$
Frequency of the integrating link ω_1 ($\omega_{1(a)}$, $\omega_{1(b)}$), [rad/sec]	125	400	200	500	180
Slice frequency (asymptotic *) ω_0 ($\omega_{0(a)}$, $\omega_{0(b)}$), [rad/sec]	250	(200*)	400	(160*)	450
Frequency ratio ω_1/ω_0	0.5	2	0.5	3.15	0.4
Actual frequency of single gain ω_0 (ω_{v0}, ω_{v1}), [rad/sec]	250	283	400	283	450
Upper connected frequency ω_2, [rad/s]	707	707	707	707	707
Order of inclination of the characteristic at $\|K(\omega)\| = 0$ dB	1	2	1	2	1

The depicted diagrams give a fairly complete picture of the features of each of the structures, explaining their work. Thus, the characteristic of the basic structure has a classical appearance, intersects the axis 0 dB at an angle of 20 dB/dec (slope of the first order) in the zone of the best phase reserve, the cutoff frequency of the system is

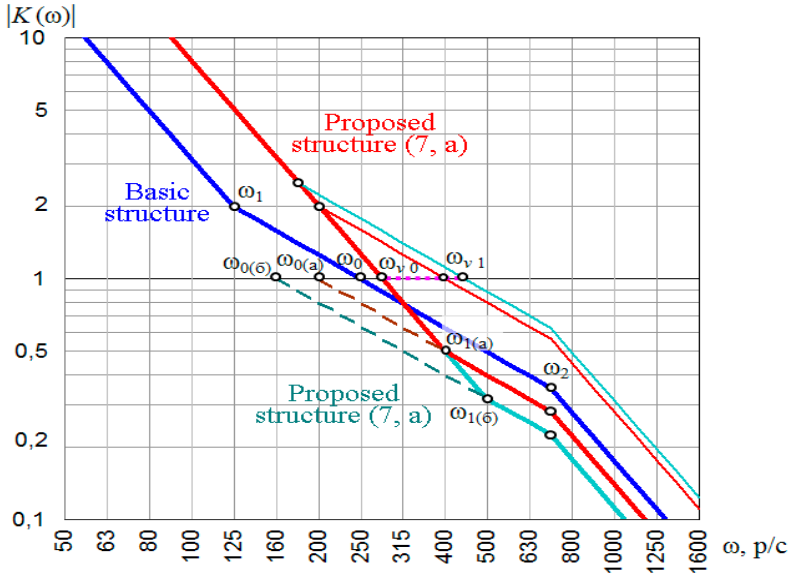


Fig. 11: Logarithmic amplitude-frequency characteristics of the studied structures.

twice the value of the lower connected frequency ω_1.

The proximity of the frequency ω_2, which characterizes the bandwidth limitation of the speed loop, did not allow the expansion of the frequency properties and improve the dynamic parameters of the tracking system in its basic configuration.

In the proposed structure, these requirements are violated in the mode of blocking the differential link. And although the frequency ω_{v0} is slightly higher than the value of ω_0, the curve of logarithmic amplitude characteristics intersects the 0 dB axis at an angle of 40 dB/dec (second order of inclination) up to unconventionally high values of the combined frequencies $\omega_{1(a)}$ and $\omega_{1(b)}$.

5 Future Research Directions

A conventional system with such parameters would be unusable, having extremely low stability and susceptibility to self-oscillations. But the proposed option 7 system in this state is only part of the operating cycle. The input factor of the differential correction k_d is modulated by the ratio of the current state of the system, in particular the deviation signals and the first and second derivatives thereof.

The input factor of the differential correction is modulated by the ratio of the current state of the system, in particular the deviation signals and the first and second derivatives thereof. Thus, the characteristic changes within the limits indicated in the diagram, crossing the 0 dB axis in the frequency range from ω_{v0} to ω_{v1}.

In the second limit case (for ω_{v1}) the characteristic acquires features sufficient to ensure a certain margin of stability, all the specific indicators for this ratio of parameters in the case of their application to the usual structure are available in the results of the study.

However, in none of the combinations of parameters in the middle of the specified range, the usual system does not acquire the desired quality indicators. The introduction of an appropriately modulated differential correction has the opposite effect - the system acquires new qualities that far exceed these indicators for the initial state of the system is improved. In addition, the adaptive nature of the change in the frequency response of the proposed system gives grounds to obtain the desired combination of low sensitivity to the action of interference with high speed.

Analyzing the characteristics in Fig. 11 we can draw the following conclusions: the proposed system compared to the base has an expanded bandwidth of 1.6-2 times, respectively, the same number of times increased gain in the open state in the upper operating frequencies, and in the low-frequency range (below 125 rad/s) the gain is increased 2.5 times.

With such changes in the frequency response of the system should expect a significant reduction in the error of tracking the controlled surface by 1.6-2.5 times depending on the spectral composition of the curve describing the surface of the part at a certain fixed speed of its bypass. At the same time, it is possible to increase the speed of the measurement process while maintaining the permissible level of error in obtaining results.

6 Conclusion

A new structure of the tracking system controller for measuring the level of wear of parts has been developed. This allows to obtain improved indicators of dynamic accuracy of automated drives in relation to the specifics of their operation in the in the information measuring complex. The method helps to solve the problem of simultaneously ensuring two conflicting requirements - high accuracy and sufficient speed of wear measurements of the part.

To solve the problem, a differential link is introduced into the controller, which generates a signal of the rate of change of deviation. The time constant of the differentiator is chosen equal to the time constant of the closed system.

The advantages of the developed system are that the signals of deviation and the rate of their change during the exponential development of the step action are the same inabsolute value and have opposite signs. This ratio is the basis of the idea of synthesis of the proposed regulator.

The proposed version of the regulator allows greater convergence of the points of the lower and upper connected frequencies to their complete coincidence, when the

normal system goes into self-oscillating mode. The proposed option remains stable, provides high-speed and high-quality transients, which is confirmed by the results of comparative computer simulations for different laws of input influence.

The most striking advantages of the proposed system are manifested in the development of a series of successive positions, for example, with multiple stepped effects. The system exhibits significantly less oscillation and operates with almost half the error compared to a conventional system.

The proposed version of the switched structure of the tracking system controller and the results of mathematical study of its operation can be used in the development of precision automated drives of automated measuring systems of high accuracy and performance, as well as other automatic control systems, where obtaining the best accuracy and speed.

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