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DEVELOPMENT OF BORING CUTTER ADJUSTMENT SYSTEM USING PIEZO ELEMENTS

The paper proposes a methodology for experimental studies of non-stationary dynamic systems LDTW (lathe-device-tool-workpiece), in particular, the control of parameter variability, increasing accuracy for measuring increments of recorded values, the predominant importance of recording equipment, the use of narrowband analyzers in measuring modulated oscillations, etc. A significant increase in the accuracy of metal-cutting machines has been achieved on the basis of experimental studies of non-stationary technological systems with variable parameters. The quality and accuracy of machining on finishing and boring machines are subject to very strict requirements. For example, deviations from roundness should not exceed 1-2.5 microns.

The technique of measuring the actual position of the cutter in the process of boring holes, the schemes of loading of the boring bar at taring and tared graphs at static loading, the technique of deciphering the trajectory of shaping on the basis of the obtained oscillograms are given. Graphs of change in the trajectory of the cutter tip motion are obtained.

Keywords: piezo element, stiffness, oscillogram, accuracy, calibration, deviation from circularity, oscillations.

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РОЗРОБКА СИСТЕМИ ПІДНАЛАГОДЖЕННЯ РОЗТОЧУВАЛЬНОГО РІЗЦЯ З ВИКОРИСТАННЯМ П'ЄЗОЕЛЕМЕНТІВ

У роботі запропоновано комплексну методику експериментальних досліджень нестаціонарних динамічних систем типу «верстат–пристрій–інструмент–деталь» (ВПІД), спрямовану на підвищення точності і надійності технологічних процесів механічної обробки. Методика передбачає контроль змінності динамічних параметрів, підвищення точності вимірювання приростів реєстрованих величин, оптимізацію апаратурного забезпечення запису сигналів та застосування вузькосмугових аналізаторів під час вимірювання модульованих коливань. Особлива увага приділена аналізу впливу зовнішніх і внутрішніх збурень на стійкість технологічної системи, що дозволило підвищити достовірність результатів та обґрунтувати заходи щодо зниження вібрацій і коливань.

Завдяки проведеним дослідженням досягнуто суттєвого підвищення точності металорізальних верстатів, що працюють у нестаціонарних режимах зі змінними параметрами. Для оздоблювально-розточувальних верстатів встановлено, що вимоги до точності обробки є надзвичайно високими: допустимі відхилення від округлості поверхонь не повинні перевищувати 1–2,5 мкм. У межах експериментальної частини наведено методику вимірювання фактичного положення різця в процесі розточування отворів, розроблено схеми навантаження борштанги при таруванні, а також побудовано таровані графіки під час статичного навантаження.

Окремо описано методику розшифрування траєкторії формоутворення на основі аналізу осцилограм, що дозволило визначити закономірності зміни просторового положення різального інструменту та отримати графіки траєкторії руху вершини різця. Результати досліджень створюють науково-практичну основу для вдосконалення технологічних процесів високоточної обробки, забезпечують підвищення стабільності розмірів і якості поверхонь деталей, а також можуть бути використані при розробці систем автоматизованого контролю і діагностики стану технологічного обладнання.

Ключові слова: п'єзоелемент, жорсткість, осцилограма, точність, тарування, відхилення від округлості, коливання.

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STATEMENT OF THE PROBLEM IN GENERAL TERMS AND ITS RELATIONSHIP TO IMPORTANT SCIENTIFIC OR PRACTICAL PROBLEMS

Mechanical oscillations during boring are the causes of shape errors in the bored holes. These vibrations are caused by the movement of the tool relative to the workpiece due to:

1. offset of the boring allowance caused by the incorrect shape of the pre-machined hole and its deviation relative to the geometric axis of the spindle due to workpiece mounting errors;

2. non-uniformity of stiffness of the spindle assembly, which is determined by non-uniformity of radial pliability at the cutter by the angle of rotation of the spindle;

3. forced oscillations of the system caused by dynamic disturbances in bearings and chip formation process;

4. deviations from the rectilinear movement of the table and the irregularity of this movement itself and other factors.

The main purpose of this work is to develop a measuring system that would automatically reduce the influence of these factors and increase the accuracy of boring holes. In this paper, based on the analysis of technical literature, different methods of dimensional adjustment of the tool to compensate for its dimensional wear, in particular, in diamond boring machines are studied.

ANALYZING STUDIES AND PUBLICATIONS

Condition monitoring of rotating turbine blades is performed by non-contact method [1]. The values of characteristic vibration parameters for real-time assessment of turbine blade condition are determined. Vibration analysis by traditional signal processing methods is supplemented by matrix transformations to refine the amplitudes and frequency of vibrations.

In the light of Industry 4.00 solutions, the performance of blade tool machining process, wear of cutters, quality of machined surface, energy consumption should be automatically monitored. The use of sensor programs and systems provides improved machining performance, reduced cutting forces and machining errors [2]. Most studies focus on vibration detection or tool wear patterns. The importance of simultaneous monitoring of the two states during the actual cutting process is emphasized [3,4].

An amplitude-phase joint analysis (APJA) method is developed for vibration measurement using a microwave sensor [5]. Estimates of the accuracy of the method are given, suggesting a promising approach to turbine blade condition monitoring.

The paper [6] describes the applications of sensor systems in hole machining (grinding, reaming, boring, drilling) using their predictive capability to improve machinability characteristics such as surface integrity, tool wear, dimensional accuracy, etc.

The dependence of the parameters of thermal processes on the frequency of mechanical vibrations, the time of their effect and the distance from the point of application of vibrations to the defective zone has been determined [7]. When cutting large thin-walled parts widely used in the aerospace industry, there are technological problems with ensuring the specified accuracy of products. This is due to the fact that under the action of cutting forces and temperature there are dimensional errors caused by the low rigidity of machined parts [8,9].

Recently, various tool holders have been designed to take into account centrifugal forces affecting tool grip accuracy and stiffness under high-speed rotation. A device has been developed that can measure the grip properties of a tool holder to provide a quantitative evaluation [10]. The developed holder system has been shown to control intermittent vibrations caused by threading and vibrations during end milling [11]. A new in-process vibration detection method for end milling has been developed. The developed system does not require any external sensors as it only utilizes the servo information of the spindle control system [12].

During deep hole boring, it is not possible to observe the working condition of the boring mandrel, so a cutting force monitoring system was developed for the deep hole boring process [13].

BASIC OUTLINE

Method of measuring the actual position of the cutter during boring of a hole

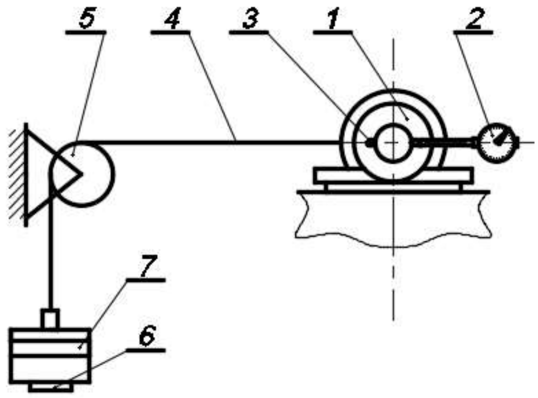
In order to control the indexing movements of the tool to improve machining accuracy, it is necessary to know the actual deviation from the roundness of the bore being bored at any given time. There are many factors that influence the non-roundness of a bore, and it is very difficult to take them into account in practice. Standard tests on finishing boring machines determine the maximum achievable accuracy of the bore shape. The quality of the boring head and the variable pliability of the spindle-boring bar system in terms of the angle of rotation have the main influence on the deviations from the roundness of the hole.

Due to the displacement of the workpiece axis, non-uniformity of the workpiece allowance, wear of the cutter, and oscillations of the entire system during chip formation, the cutting forces acting on the cutter change significantly per revolution. The change in the forces acting on the cutter leads to a continuous change in the deformation of the boring bar. The most significant change in the position of the tool tip relative to the axis of rotation is due to bending deformations in the direction of the tool axis. In this connection, the measurement of the bending deformation of the boring bar during the cutting process will make it possible to judge with some approximation the change in the shape-forming trajectory of the tool tip. Geometric inaccuracy of spindle rotation and non-uniform stiffness in the angle of rotation when the workpiece is rotating will also lead to changes in the initial allowance.

Strain gauges were used to record the change in the deformation of the boring bar. The highest bending strain can be recorded at the base of the boring bar. Therefore, two strain gauges were glued from two opposite sides on the cylindrical part of the boring bar at its base. The sensors are located in a plane passing through the axis of the cutter and the boring bar and are connected in a half-bridge. The second half-bridge is located in an eight-fold amplifier. The unbalance signal is amplified and recorded by an arrow or optical galvanometer. An oscilloscope H700 was used to record the change in the strain value during cutting.

Calibration of the measuring system

To tare the stiffness of the elastic system, a special rod is inserted into the boring bar instead of a cutter, to which a kapron thread, thrown over the bracket, is attached. To the opposite end of the thread is attached a sub-plate, on which weights are placed successively. A change in the deformation of the boring bar causes the strain gauge bridge to become unbalanced. The signal is received either on the arrow device or on the loop of the oscilloscope H700. The scheme of loading of the boring bar during calibration is shown in Fig. 1



1 - boring bar; 2 - indicator with a division value of 0.001 mm; 3 - rod;
4 - kapron thread; 5 - block with bracket; 6 - platen; 7 - weights.
Fig. 1. Scheme of loading of the boring bar during calibration

To record the displacement of the tool tip under load during the taring process, the tip of an indicator with a graduation value of 1.0 μm is brought into contact with the pulling rod from the rear side. The indicator itself is attached to a stand mounted on the table mirror.

Fig. 2. shows the load - displacement graph, and Fig. 3. graph of the cutter tip displacement - deviation of the oscilloscope loop bunny. Using the latter graph, it is convenient to decipher the oscillograms that record the deformation of the boring bar and the displacement of the cutter tip.

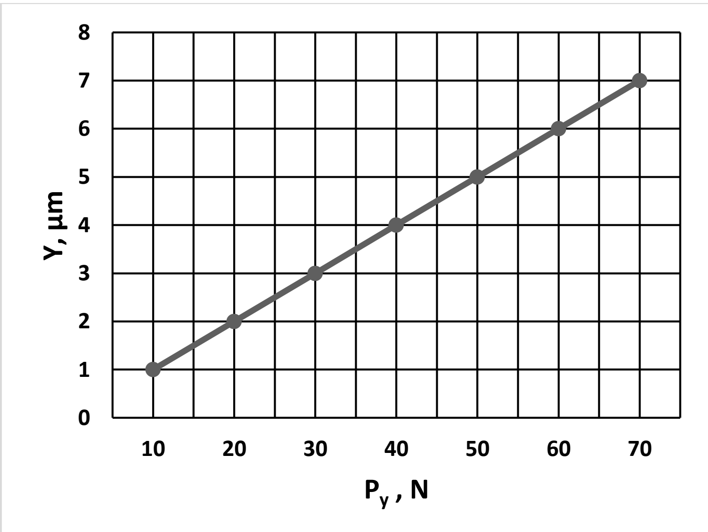


Fig. 2. Tare graph of boring bar deformation under static load

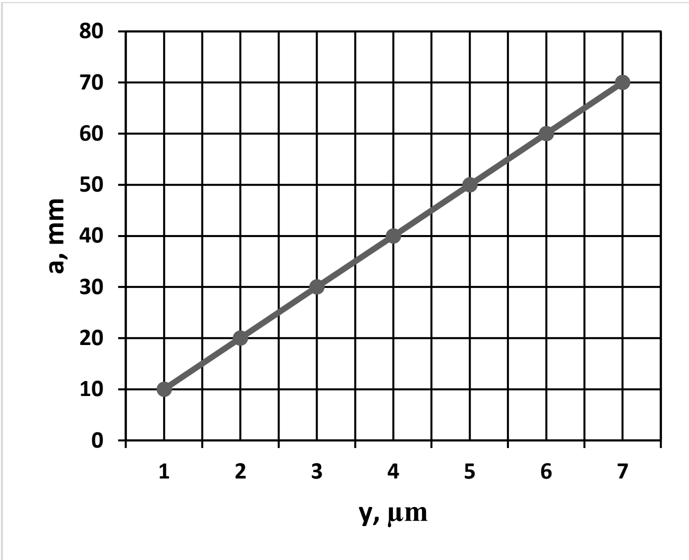


Fig. 3. Graph of the oscilloscope loop light bunny deviation as a function of the cutter tip displacement

In order to estimate the change of the forming trajectory per one spindle revolution, it is necessary to clearly record the boundaries of one revolution on the oscillogram. For this purpose, a marker is mounted, which works on the principle of generating EMF in a coil with a core, past which a permanent magnet moves.

Deciphering the trajectory of shaping using captured oscillograms

Fig. 4 shows an oscillogram taken during boring of a bushing made of steel 45 in the following mode: V=160 m/min; t=0.1 mm; S=0.07 mm/rev. Parameters of boring bar: diameter d=28 mm; L=80 mm. Using the tare graph, we translate the obtained deviations on the oscillogram into linear displacements of the boring tool tip.

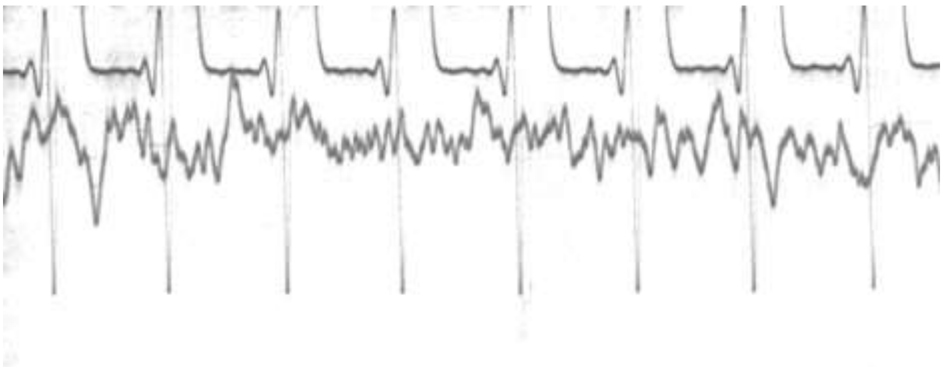


Fig. 4. Oscillogram showing the change in the position of the cutter tip during cutting of a pre-deformed workpiece

To evaluate the influence of the offset allowance on the forming trajectory, before taking an oscillogram, the center of the workpiece hole is shifted relative to the spindle rotation axis by 0.05 mm by creating an artificial eccentricity. The amount of the offset was monitored using a micron indicator. Creation of the offset caused characteristic deflections of the boring bar recorded on the oscillogram.

To obtain a visual picture of the circular trajectory change for one spindle revolution, a circular graph was plotted. The method of its construction was as follows. The length of the oscillogram segment corresponding to one spindle revolution and the length of the circumference of the bored hole was substituted. The circle was drawn to a larger scale and divided by radial rays evenly into 12 or 24 parts. The oscillogram segment corresponding to one revolution is divided into the same number of parts. On the radial rays of the oscillogram, the ordinates of deviation y_1; $y_{(2)} \dots y_{12}$or y_1; $y_{(2)} \dots y_{24}$ are laid off inward from the base circle (the boring bar deflection causes the reduction of the boring hole). By connecting the obtained points with a smooth curve, we get a graphical representation of the forming trajectory.

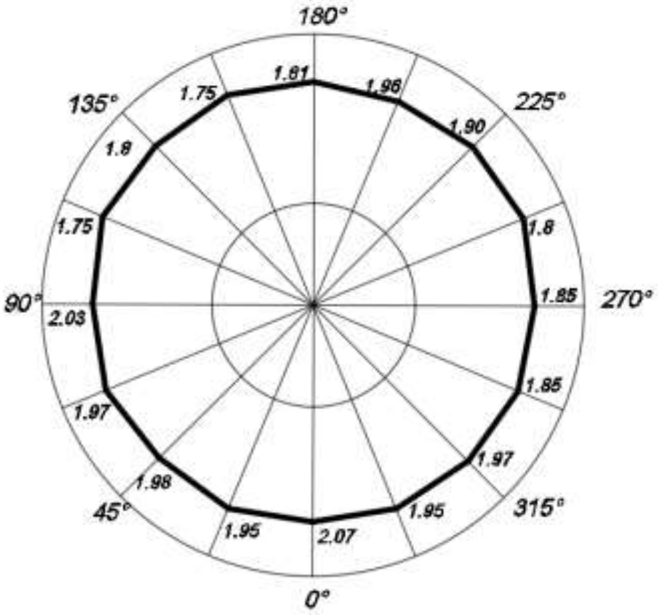


Fig. 5. Circular plot of the torch tip trajectory variation. Values of deviations from the specified diameter are given in micrometers

Development of piezoelectric transducer of small adjustment movements of boring cutter

For small movements to correct the geometry of the boring hole, a transducer that can operate at frequencies of 50-100 Hz is required. Any mechanical systems due to their inertia are of little use for controlling rapidly changing processes. In this connection, based on the analysis of possible adjustment systems, an attempt was made to create a piezoelectric transducer of small displacements.

For piezomaterials of the PZT group, the dimensional variation at a constantly applied voltage is not thousandths but hundredths of microns, which is also insufficient for tool adjustment. In the resonant mode, the amplitude of size variations of PZT plates reaches several microns.

The resonant frequency depends on the dimensions of piezomaterials or a package of piezoelements and the stiffness of the transducer. Thus, flat piezoceramic transducers are plates (rectangular or circular shape) made of piezoceramic material, the thickness of which is equal to half of the wavelength λ/2. Under this condition, the plates oscillate at the fundamental frequency. The frequency of plate oscillation is determined by the formula:

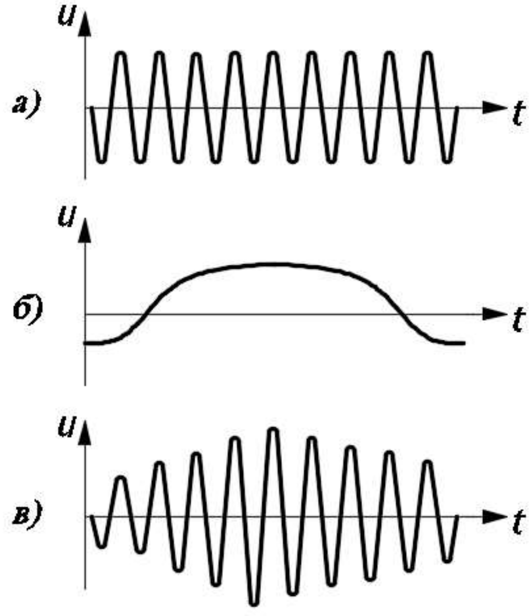
$$f = C/\lambda = C/(2l) \quad (1)$$

where *C-velocity of* elastic volitions in the plate.

As we can see, this formula does not take into account the way the plates are fixed in the transducer. It is valid only for a single piezo plate.

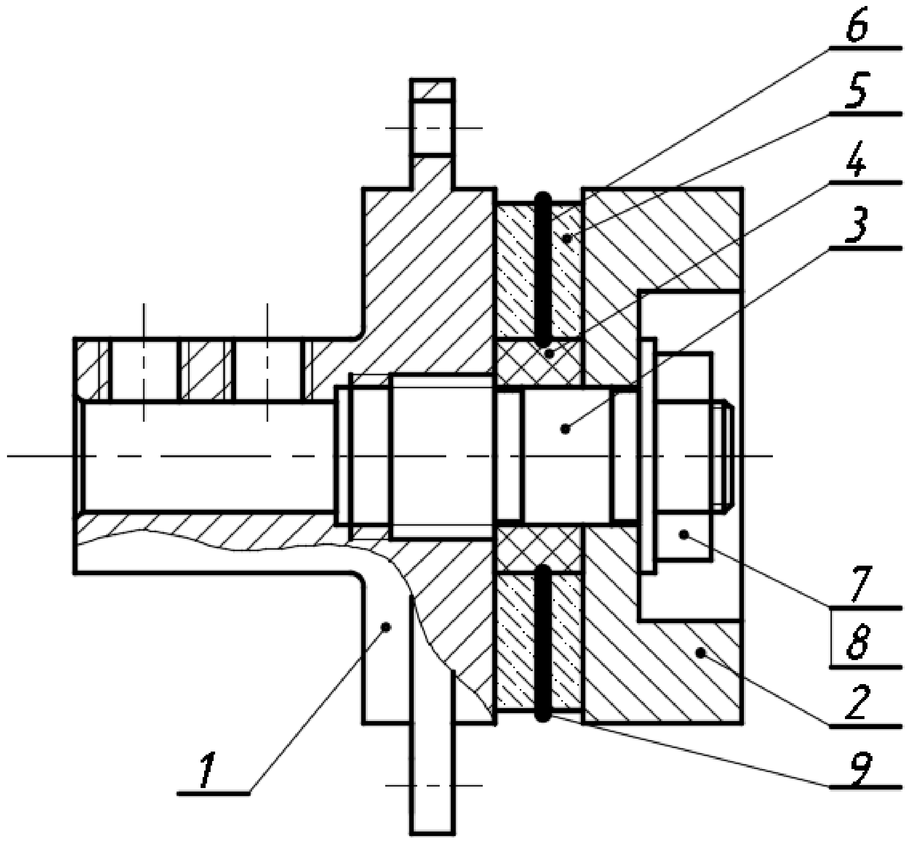
In a composite packet radiator, its constituent elements alternate in the following sequence: metal pad, piezoplate, pad, piezoplate, pad (Fig. 7). Thus, the piezo plates are not in the middle of the system in the strain beam. The middle pad separating the piezoplates can have a weakened cross-section. Then the length of the transducer is noticeably less than $\lambda/2 = C_{(1)}/(2f)$, where *f is* the operating frequency and $C_1$is the ultrasonic propagation velocity in the overlay metal.

However, piezoelectric transducers acceptable for the dimensions of boring bars have a high resonant frequency (22...40 kHz). Therefore, to obtain sub-tuning oscillations of the cutter with a frequency of the order of tens and hundreds of Hz, it remains to use the method of amplitude modulation: the piezoelectric transducer will operate at the resonant frequency, and these oscillations must be superimposed with voltage oscillations, which are a function of the hole non-roundness (Fig. 6).



a - carrier frequency; b - signal of the sensor measuring the hole shape error; в - trim signal
Fig. 6. Principle of amplitude modulation

Based on the above, the design of the piezoelectric transducer is developed, the scheme of which is shown in Fig. 7. Such a piezoelectric transducer has sufficient strength to be used as an actuator for moving the cutter in the cutting process, since the piezoelements have a sufficiently high compressive strength.



1 - toolholder; 5 - disk of piezoelectric material; 2 - back plate; 6 - gasket; 3 - stud; 7 - nut; 4 - bushing; 8 - washer; 9 - conductor rail
Fig. 7. Design of ultrasonic piezoelectric transducer for tool movement during boring operations

The transducer is a prefabricated structure for operation in the mode of high-frequency oscillations with a resonance frequency of about 40 kHz. The structure consists (Fig. 7) of a toolholder 1, two disks of piezoelectric material 5, which are compressed with the help of a stud 3. The mass (including the cutter) of the entire system is designed for operation in the resonance mode.

An ultrasonic industrial generator was used for its preliminary testing. The operating amplitude of the oscillations was 10 μm. This amplitude is quite sufficient to realize a change in the position of the cutter when controlling deviations from the roundness of the hole.

The second stage of the experiments is to install the system on the machine and test it under load. For this purpose, a special support bracket of high rigidity was made instead of the boring bar to simplify the tests. The general view of the complete system is shown in Fig. 9, and the block diagram of the sub-adjustment control is shown in Fig. 8.

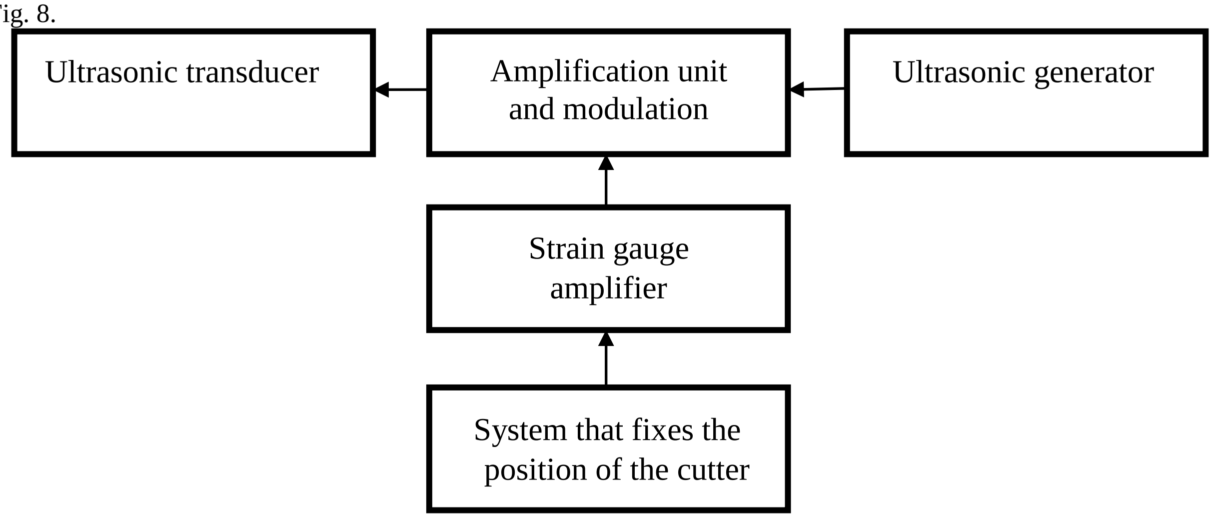


Fig. 8. Basic block diagram of the sub-adjustment control

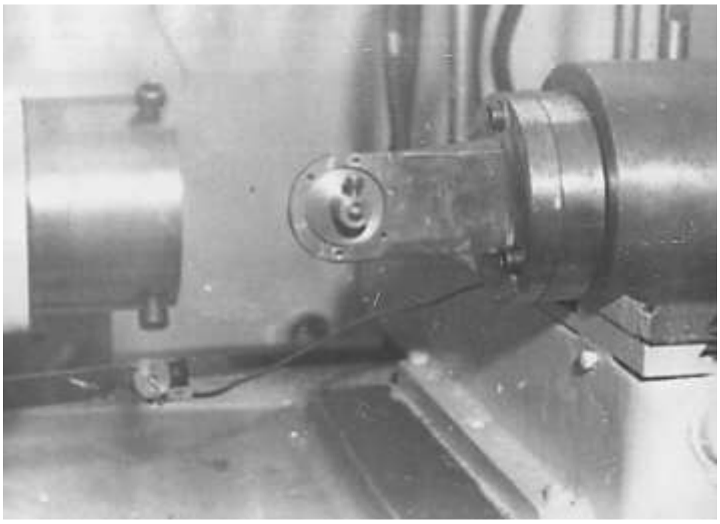


Fig. 9. Bracket with ultrasonic piezovibrator mounted on diamond boring machine

The system must undergo extensive load testing at various modes.

CONCLUSIONS FROM THIS STUDY AND PROSPECTS FOR FURTHER DEVELOPMENT IN THIS AREA

This study investigated and analyzed the main factors that cause mechanical vibrations during boring, which in turn lead to shape errors in the bored holes. These factors include stock displacement, uneven spindle stiffness, forced vibrations caused by dynamic disturbances, and deviations from straight table motion.

In order to improve the accuracy of boring, a method of measuring the actual position of the cutter during machining was developed. The use of strain gauges made it possible to record changes in the bending deformation of the boring bar, which is an approximate indicator of the change in the shape-forming trajectory of the tool tip. Thanks to this technique, graphs linking load to displacement and the trajectory of the cutter tip with the modulated signal were obtained, which makes it possible to decipher oscillograms and quantify deformations.

Based on the data obtained and oscillograms recorded during boring, the possibility of graphical representation of the forming trajectory in the form of a circular graph was demonstrated. This makes it possible to clearly assess the influence of various factors, such as stock displacement, on machining accuracy.

The next stage is to carry out comprehensive tests of the developed system on the machine under real loads and various cutting modes. This will make it possible to evaluate its stability, reliability and accuracy under conditions that are as close as possible to production conditions. The developed system will be integrated into the general concept of Industry 4.0, which implies automatic control of productivity, tool wear, quality of the machined surface and energy consumption. This will make it possible to create fully automated and adaptive machining systems.

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