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MECHATRONIC TECHNOLOGICAL SYSTEM INFORMATION SUPPORT**Vasily P. Larshin**ORCID: <https://orcid.org/0000-0001-7536-3859>; vasilylarshin@gmail.com**Anatoly M. Gushchin**ORCID: <https://orcid.org/0000-0002-1289-9557>; guschinanatoliy1@gmail.com

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ABSTRACT

The article focuses on a new way to solve the problem of cutting processing due to the appearance of a wide range of superhard and hard-to-machine structural materials for aircraft, automobile, ship and engine construction, as well as for spacecraft, medicine (orthopedics, dentistry), nuclear and military equipment. Such materials have an organized regular structure, high strength, superhardness. As a result, there is a problem of defect-free machining of these materials without damaging their balanced structure. The article describes a new approach and formulates innovative principles for creating a new class of mechatronic technological systems for precision machining of parts made of these materials using the example of drilling small diameter deep holes. The core of the mechatronic technological system is a mechatronic parametric stabilizer of the power load on the cutting tool. The mechatronic technological system provides a program task, automatic stabilization and maintenance in the tracking mode of the power load on the cutting tool with “disturbance control”. For example, in the technological cycle of drilling small diameter holes, such a system protects the drill bits from breakage. An integrated technological system is proposed with the following three levels of control: intelligent (upper), adaptive (middle) and robust (lower). The basis of the multi-level system is a high-speed robust automatic control system “by the disturbance”. The disturbance is the load torque, which is either automatically stabilized, or tracked when setting a program from a computer, or changes according to the program that sets the mechatronic technological system the functioning (operation) algorithm. This algorithm can vary widely with different methods of machining parts by cutting (grinding), including shaping free 3D surfaces according to their digital models. The mechatronic technological system proposed is easily integrated into the cutting (grinding) system of CNC machines, expanding their capabilities by transferring the standard control program of the CNC to a higher level of the control hierarchy. This allows machining any complex-shaped parts, including “double curvature” parts, namely impellers, turbine blades, rowing screws, etc.

Keywords: Mechatronic System; Information Support; Linear Electric Motor; Electrodynamical Coupling; Drilling Holes; Complex-Shaped Surface; Defect-Free Machining

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1. INTRODUCTION

It is obvious that every operation, as part of the process, should be automatically regulated at every moment of time. This means that the current technological transformations must be carried out on time, i.e. with a minimum time delay. Automated technological systems with CNC are made on the basis of a frequency-controlled electric drive with vector control. They are multi-circuit and have certain inertia even when using the principle of subordinate regulation, i.e. with feedbacks in current, speed and position. Therefore, the sequence of technological actions covered by negative feedback (deviation control) has a time delay by definition.

Defect-free machining of superhard and special materials on traditional (non-adaptive, non-

intelligent) metal-cutting equipment is often impossible. It is obvious that each new material (composites, ceramics, synthegran, sitall, plastics, porous materials, superhard materials, titanium and cobalt-chromium alloys, zirconium dioxide, etc.) requires automatic adjustment to the optimal operating mode in the conditions of the corresponding technological system. A mechatronic technological system (MTS) of this type will be considered in this article as an example for building a technological system with multi-level control.

In this article, the following technical solutions are proposed for building a fast-acting MTS: the principle of disturbance control and hierarchical (multi-level) control. The functioning algorithm of such a system should be planned and implemented at different levels of the hierarchy.

In 1972, a group of scientists from the Moscow Machine Tool Institute under the leadership of prof.

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B. S. Balakshin was awarded the Lenin Prize for a set of works that explored new ways to improve the accuracy and productivity of cutting (grinding) on machines using adaptive systems. Similar studies in those years were conducted by a group of scientists of the Kuibyshev Polytechnic Institute under the leadership of prof. Mikhelkevich V. N. (electric drive department) in relation to grinding machines operating by the plunge method. In the same years, scientists of the Perm Polytechnic Institute under the leadership of the head of the Mechanical Engineering Technology Department prof. Yakimov A.V. developed and brought to serial production a system of automatic regulation of the power load on grinding wheels during gear grinding on MAAG-type machines. These machines work with two dish grinding wheels by the tooth generation method. The success was made possible thanks to the cooperation of three departments: mechanical engineering technology, automation and telemechanics, as well as physics. Since then, the idea of adaptive control has become firmly embedded in the technological research of scientists and technologists.

However, in general, despite the seemingly promising idea of automatic control with load feedback, this idea has not found industrial application for a number of reasons. One of the significant reasons for this state of affairs was the so-called dynamic complexity of the closed circuit of the automatic control system. The increment of the load on the cutting tool with a certain delay is recorded by the load sensor. This load is controlled, for example, by the power of the electric drive of the grinding wheel. For machines operating with a blade tool, the dynamic complexity of the control object is further increased, since a mechanical gearbox is included in the drive chain of the workpiece or cutting tool being processed for discrete dosing of the machine's operating parameter. This negatively affects the automatic control quality: the gain of the open-looped system decreases, the dynamic delay increases. All this is characteristic of the so-called principle of deviation regulation.

In this article, it is proposed to use the second of the two known principles of automatic control, namely, disturbance control. A disturbance in systems of the type described is the unexpected increase in load that arises in the contact zone between the cutting tool and the workpiece. The sensitive ele-

ment for controlling this disturbance is a part of the mechatronic load stabilizer, on the basis of which the tracking and program subsystems of automatic disturbance control are made. Such a construction of the system lower level – a robust automatic control system – makes it possible to provide for the middle (adaptive system) and the upper (intelligent system) control levels. This type of mechatronic load stabilizer can be built into the technological system of existing CNC metal cutting machines with an open architecture.

2. LITERATURE REVIEW

2.1. General

The literature analysis was carried out from the position of automatically controlled cutting processes and taking into account the possibility of multi-level control [1]. At the lower level of the hierarchy, the control device performs automatic robust control. Adaptive and intelligent control is performed at the middle and upper levels, respectively (Fig. 1). However, the principles of operation and the structure of these subsystems are not disclosed.

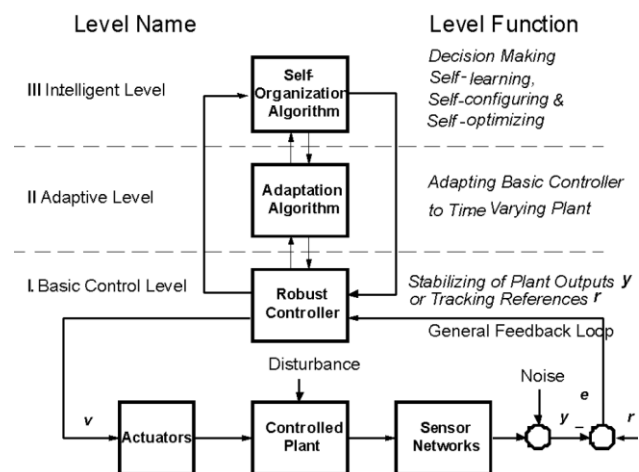


Fig. 1. General configuration of three levels hierarchical control system [1]

Source: [1]

Drilling of small diameter holes with the use of special cutting lubricants [2] by definition requires the adaptation of drilling parameters, in which the best workability of the material is observed, depending on the chemical, physical, and mechanical properties of lubricants. However, traditional CNC machines do not have the ability to control the cutting conditions.

When developing MTS, it is reasonable to use the principle of adaptation known in the living nature, which is performed when the cutting control

system interacts with a non-deterministic environment. This is noted when considering configurable control devices (vehicles) [3] and in the fundamentals of mechatronics [4]. For example, when drilling holes in printed circuit boards made of fiberglass, high temperature in the cutting zone leads to delamination of the package of compressed plates [5].

Artificially created structural materials, in particular polymer-composite (PCM) based on high-strength carbon, boron, glass, organic and other fibers, receive unique physical and mechanical characteristics with a regular structure during their manufacture. Due to their high strength, these materials are used in aerospace vehicles, aircraft construction, the automotive industry, radio electronics, medicine (orthopedics and dentistry), nuclear and military equipment. All this is reflected in the numerous references on this issue. When analyzing these references, the main attention is paid to methods, technologies, technological systems and control systems, thanks to which the unique physical and mechanical properties of these materials are least damaged during mechanical processing by cutting (grinding) these materials. For example, violations of the unique properties of PCM include the following violations [6]: (1) loosening of the reinforcing dielectric base of the glass fiber which is a significant obstacle to the subsequent metallization of the holes; (2) vitrification of the binding dielectric base, which leads to a deterioration in the mechanical strength of the soldered joints; (3) formation of collars at the entrance and exit of the drilled hole.

The most significant drilling factors affecting the quality of the mechanical operation are the following [7]: technological capabilities of special CNC machines for drilling printed circuit boards; properties of PCM used in the manufacture of printed circuit boards.

Special CNC machines have a spindle speed of 80-150000 rpm, the tool life is 1000-2500 holes with a diameter of 0.1-0.5 mm. Machining is performed with drills made of hard alloy. However, these machines are not equipped with robust and adaptive control means to optimize operation and eliminate drill bit breakage. A wide range of the PCM names having various physical and mechanical characteristics leads to the need for flexible changeover (readjustment) of these CNC machines. This changeover is still performed manually without taking into account the individual drilling conditions for each drill

bit. This technology cannot provide automatic load stabilization on a drill. Therefore, the program control and tracking mode for optimizing the cycle of defect-free drilling of holes are not possible under these conditions. When drilling holes in carbon fiber-reinforced polymers, even on modern foreign CNC machines, the disadvantages noted above arise despite the high quality of this automated equipment [8].

Problematic issues require a systematic approach to their solution. For this purpose, the following principles are formulated [9, 10]: (1) “machine – tool – material to be machined” is an integrated cutting (grinding) system with interdependent movements that are supported by information and energy flows; (2) the regularities of mutual displacements in the specified cutting (grinding) system are determined by the corresponding laws of equilibrium of solids in space; (3) mutual adaptation of movements in the system is intensified by the imposition of vibrations on the movement of the instrument; (4) vibrations should be controlled.

These principles lead to the solution of the problem of creating reciprocating movements of the cutting tool with an adjustable frequency and amplitude. However, the anisotropy of the properties of these materials does not allow for their defect-free machining, i.e. without violating the specially created structure of the material and its balanced state. Therefore, the control of the reciprocating movement of the cutting tool must be carried out in a self-adapting mode based on the principles of adaptation and intelligent control [11].

Mechatronics is a convergent scientific and practical discipline [12] and at the same time a computer paradigm for the development of technical cybernetics [13] and robotics [14]. The presence of mechatronic elements in modern cutting (grinding) systems is a characteristic feature of high-tech products that are created using these systems [15]. Mechatronic systems of the lower level are able to influence the method of correcting the cutting parameters in CNC systems [16].

2.2. Multilevel management in living organisms

It is possible to combine the performance of a robust lower-level system with adaptation and intelligent control in a hierarchical control system that takes place in living organisms. For example, all movements of the human body, from blinking to

walking or jumping on one leg, are carried out at the expense of two main departments of the nervous system – the pyramidal and extrapyramidal systems [17]. The pyramidal system is a rough regulation of movement, and the extrapyramidal system is a very fine-tuning of the motor act, manifested by the correction of muscle tone, coordination and accuracy of the movement performed. The defeat (failure) of the extrapyramidal system leads to the development of various disorders, manifested by the occurrence of involuntary movements, such as tremor, dystonia, chorea, tics, and so on.

Motor commands are transmitted along extrapyramidal pathways (tracts) with protective motor reflexes that proceed unconsciously. For example, due to extrapyramidal pathways, information is transmitted when restoring the vertical position of the body as a result of loss of balance (vestibular reflexes) or during motor reactions to sudden light or sound effects (protective reflexes that are closed in the midbrain roof), etc. The information transmission channel is a cluster of efferent nerve fibers from the upper motor neurons that come from the cerebral cortex and end either in the brain stem (corticobulbar tract) or in the spinal cord (corticospinal tract) and are involved in the control of motor functions of the body. An example of a classic violation of the pyramidal system is a stroke, which results in paralysis of the limb. In other words, the failure of the upper-level system leads to the paralysis of the lower-level system.

Having a robust control system at the lower level of the control hierarchy [18], it is possible to create technical solutions for the middle (adaptive control) [19, 20] and upper (intelligent control) levels. The latter is carried out using genetic algorithms [21, 22], using intelligence in data processing [23], training [24], data management [25], monitoring [26], analysis [27], intelligent programming [28], and in implant production [29].

Thus, at present, the problem of sensitivity and speed of automatic systems has become very relevant due to the intensive introduction of new artificially created materials into industry and medicine, for example, materials with a specially organized layered structure (titanium with carbon fiber, ceramics, PCM), as well as wear-resistant materials such as titanium and cobalt-chromium alloys, zirconium dioxide. The latter are used for the manufacture of implants in orthopedics and dentistry. Other hard-to-

machine materials are also widely used: synthegran, sital, special plastics, porous materials, grown superhard crystals, and others. Machining of these materials on traditional machines is extremely difficult and characterized by high labor intensity; it requires flexible optimization of cutting parameters, which cannot be implemented both manually and on conventional CNC machines.

The purpose of the article is to develop a mechatronic technological system (named MTS), the core of which is the lower level of control – a robust system of automatic control “by disturbance” (i.e., by the load on the cutting tool) – and which allows organizing the middle (adaptive control) and upper (intelligent control) levels of control.

3. RESEARCH METHODOLOGY

3.1. General

The founders of mechatronics repeatedly emphasized the similarity of mechatronic systems with the systems of a living organism. For example, technical information sensors correspond to human sensory organs. The MTS design proposed below has also some analogy with a living organism. For example, the mechanism of human movement is represented in the form of a mechatronic linear motor (described below), which has two movable electric armatures that impart to the tool reciprocating movements which is characteristic of human hands.

With the appropriate information and energy combination of all the above features, MTS as a whole acquires the ability to act like a living organism, i.e. it performs “reasonable” movements, self-learns, and perceives commands from higher levels of control, for example, from the level of technological preparation of production. This allows realizing the optimal control of machining at any time, for example, when drilling holes in parts made of superhard and difficult-to-machine materials, including such materials that will appear in the future.

These features of modern technology require such cutting (grinding) process automation, which at high productivity will provide the required machining quality, taking into account both the actual machinability and anisotropy of the properties of these materials. Such requirements can be implemented only by high-speed MTS when organizing multi-level control based on the use of automatic systems of a new type, i.e. without feedback on deviation. This follows from the analysis of literary sources.

The executive mechanism of a robust automatic control system by disturbance should perceive the fluctuation of the cutting torque not as a random factor, but as a signal for an instant change in feed, i.e., simultaneously with the disturbance occurrence its compensation is carried out within the powers of the lower control level system (without involving the middle and upper control levels).

In addition, to intensify the cutting process, sometimes (when it’s necessary) a continuous feed of the cutting tool with axial vibrations superimposed on this feed (drilling with vibration) should be provided. To do this, the cutting tool must be affected by forces containing a constant and a variable component at the same time. In this case, the lower-level system implements the principle of operation of “configured control vehicle” [3].

Automatic regulation is a branch of the more general science of control – cybernetics. The control is understood as a set of actions that ensure the operation of a system based on the achievement of a pre-determined goal without the participation of the operator. The modern understanding of the essence of automatic devices is based on the concept of an algorithm. The algorithm for an automatic device (functioning or control) is an information description of the processes of functioning or control (Fig. 2, Fig. 3 and Fig. 4). The formal means for such a description are diverse: spoken language, graph (diagram), formulas, diagrams, etc.

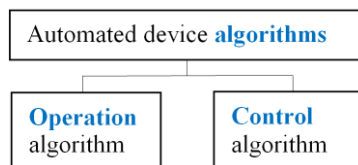


Fig. 2. Two kinds of algorithms for automated device

Source: compiled by the authors

3.2. Development of an automatic device for control by disturbance

The following principles were used in the development of a mechatronic device.

1. Elimination of the rigid connection between the tool rotation speed n (rpm) and its axial feed S (m/min).
2. Taking into account the features of the drilling process implementation in anisotropic materials.

3. Separation of the process power parameters, for example, when drilling – separation of the axial force and the cutting torque.

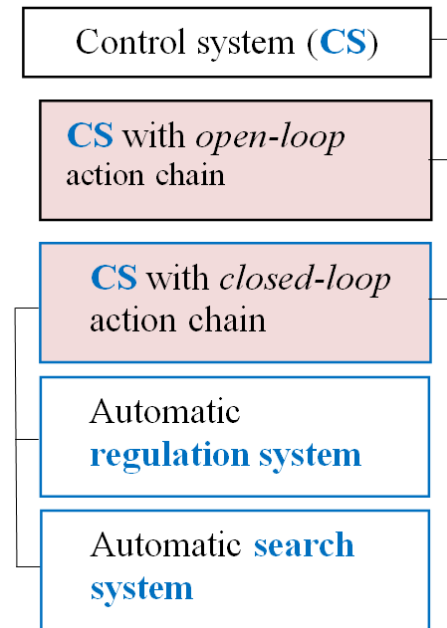


Fig. 3. Classification by the nature of the control algorithm

Source: compiled by the authors

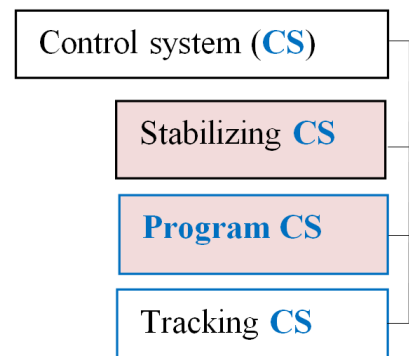


Fig. 4. Classification by the nature of the operation algorithm

Source: compiled by the authors

4. Implementation of the deep drilling process without breaking the cutting tool (automatic diagnostics of the tool state).

These new MTS properties are implemented by an experimental mechatronic head (Fig. 5) installed on a 3-coordinate CNC machine (Fig. 6).

The part to be machined is fixed and machined in a cuvette (Fig. 6), which is filled with water-based liquid to eliminate dust formation during cutting, improve the workability of the material and in order to ensure environmental safety and occupational health.



Fig. 5. Experimental mechatronic head

Source: compiled by the authors



Fig. 6. Mechatronic technological system (MTS) based on a 3D CNC machine

Source: compiled by the authors

The head control is synergistically combined with the CNC system of the machine into a single MTS, which made it possible to implement not only adaptive, but also intelligent control of all functional movements of the cutting (grinding) tool with simultaneous control of pre-set cutting power parameters.

With the help of MTS, it is possible to carry out not only defect-free drilling, but also milling (grinding) surfaces of any shape (e.g., biomedical implants) and making exclusive products that have artistic value (Fig. 7): bas-reliefs, sculptures, etc., including ones made from super-hard materials.

3.3. Description of the schematic diagrams of the device

Schematic diagrams of the electromechanical part of the MTS are shown in Fig. 8, Fig. 9, and Fig. 10. Power tool head (Fig. 8) contains a linear DC motor 1 (hereinafter LM) and a programmable electrodynamic coupling 2. These elements (1 and 2) are



Fig. 7. Exclusive products made of mammoth tusk (a, b) and optical glass (c)

Source: compiled by the authors

structurally combined with the drive motor 3 for tool 4, and by the information channel – with a computer 5. The function of the LM is the creating forces F_1 and F_2 which are acting in opposite directions either according to a program set by the computer, or according to the signals of the linear displacement sensor of the movable armature of the coupling 2.

The function of the coupling 2 is to compare the forces acting on the tool in the cutting zone with the driving forces acting on the same tool from the side of the LM and the drive motor 3. The coupling 2 is structurally made in the form of safety cam and ball clutches which are widely known in engineering. The principle of operation of such a coupling is to balance the forces and torques of working machines by forcefully closing the coupling halves through the clutch elements, for example, with the help of springs. The geometric parameters and compression forces of the springs determine the value of the maximum permissible load torque which cannot be changed during operation. A distinctive feature of the coupling 2 is the use of electrodynamic programmable forces instead of using springs.

The computer 5 function is to control the electrodynamic forces inside the entire MTS through the interface blocks 6, 7, and 8 which perform energy and information exchange between the MTS mating structural elements.

For an adequate response of the entire device to the control signals of the computer 5, linear displacement sensors 9 and 10 are provided which are mounted on the movable elements of the device (Fig. 8).

Preparation for the MTS operation, e.g., for drilling materials with any previously unknown physical and mechanical characteristics (the control object for a robust automatic system) contains the

following stages (for the middle and upper levels of control).

1. Selection of the tool type and material for its cutting part.
2. Setting the cutting speed for the selected tool (e.g., drill bit).
3. Calculation of permissible axial and bending-torsional mechanical loads on the drill with their simultaneous action.
4. Recalculation of permissible mechanical loads on the drill bit into equivalent electrical parameters of the LM and the coupling.

The permissible force value can be determined by the Ampere law, i.e.

$$F = B \cdot I_F \cdot l, \quad (1)$$

where: B is the induction in the working gap of the LM, T; I_F is the current in the armature winding, A; l is the length of the armature winding, m.

Then for the LM, the force setpoint value $[F]$ will be

$$[F] = B \cdot I_{FLM} \cdot l. \quad (2)$$

where I_{FLM} is the setpoint for the current in the armature winding, A.

Hence, we have

$$I_{FLM} = \frac{[F]}{B \cdot l}. \quad (3)$$

The torque M for the coupling is

$$M = \frac{D \cdot B \cdot I_M \cdot l}{2 \left[\tan(\alpha - \varphi) - \frac{D}{d} f \right]}, \quad (4)$$

where: D is the diameter of the coupling along the centers of the balls, m; I_M is the current in the coupling armature winding, A; d is the diameter of the seat for the movable coupling half, m; α is the angle of the conical recesses under the balls in degrees; φ is the rolling friction angle in degrees; f is the sliding friction factor.

Hence, the setpoint value $[M]$ for the load torque will be

$$[M] = \frac{D \cdot B \cdot I_{MC} \cdot l}{2 \left[\tan(\alpha - \varphi) - \frac{D}{d} f \right]}, \quad (5)$$

where I_{MC} is the setpoint for the current in the coupling armature winding, A.

Hence, we have for the current setpoint

$$I_{MC} = \frac{2[M] \left(\tan(\alpha - \varphi) - \frac{D}{d} f \right)}{D \cdot B \cdot l}. \quad (6)$$

5. Development of the MTS operation algorithm in the form of a mathematical model of the drilling cycle on the basis of which a control program for a computer is made.

The mathematical model is made up at the upper control level; it is corrected (adjusted) during the MTS operation, i.e. during the operation of a low-level tracking system (robust control). Such a control program (for the changing in the power load during the drilling cycle of one hole) can be made even without a mathematical model, using the well-known method of programming industrial robots [4]. According to this method, programmable robots can memorize and then programmatically reproduce the movements of a person teaching the robot. For example, to take items, move them to the right place, perform assembly, etc. In this case, an experienced machine operator is offered to carry out the deep drilling process based on his production experience in such a way as to ensure that the requirements for the accuracy of the hole to be drilled and both the quality of its surface and surface layer are guaranteed. For example, the features of some materials to be machined are shown in Fig. 8 by the letters: A -heat-resistant steel, B -synthegran, C -fiberglass.

All the performed actions of the operator are recorded and clocked at the interval of the drilling cycle of one hole. In particular, the operator's techniques are recorded when a drill begins the cutting, then the steady drilling process is recorded, and then the end of process is recorded also. For example, such techniques as periodic withdrawal of the drill bit from the machining zone based on his technological considerations with the slowing down the feed when the drill bit tool exits, etc. The reasons for certain actions of the operator may be purely subjective, for example, he felt the vibrations of the drill bit, heard a sound which is not characteristic for normal operation of the drill bit, felt the smell of overheated cutting lubricoolant, etc. The recording of all these actions of the operator is converted into a possible initial version of the MTS functioning algorithm and then into a control program. This MTS functioning

algorithm will be then optimized by the iteration method in the self-learning mode of a multi-level MTS as knowledge accumulates. In MTS working, this algorithm, e.g., in the kind of a graph of changes in the load which is acting on the drill bit during the drilling cycle, will be a variable setpoint of the tracking system operating according to “the disturbance control”. According to this algorithm, the current strength in the control windings of the LM and the coupling will change as follows

$$F_1 = f_1(I_1, L); F_2 = f_2(I_2, L); M = f_3(F_3, I_3, L).$$

where L is the length of the working stroke of the tool, mm; I_1 , I_2 and I_3 are the currents in the corresponding windings, A.

4. RESULTS

4.1. Description of the device operation

The mechatronic device of the lower level of the MTS works as follows (Fig. 8).

1. In the initial state, the linear displacement sensors of the LM and the coupling must have zero readings, and the drill bit must be located from the workpiece at the required initial distance.

2. A cycle control program is entered into the computer and the tool rotation drive is turned on at the same time.

3. When the program is started, forces F_1 and F_3 occur on the windings of the LM and the coupling.

4. In accordance with the MTS functioning algorithm, the moving elements of the system perform working movements, i.e. the tool moves to the part, and the coupling moves in accordance with the readings of its sensor “-1”.

After touching the workpiece with a drill bit, the plunge cutting process of the tool into the workpiece begins and then there is an output to the nominal cutting force F_1 , the value of which is changed

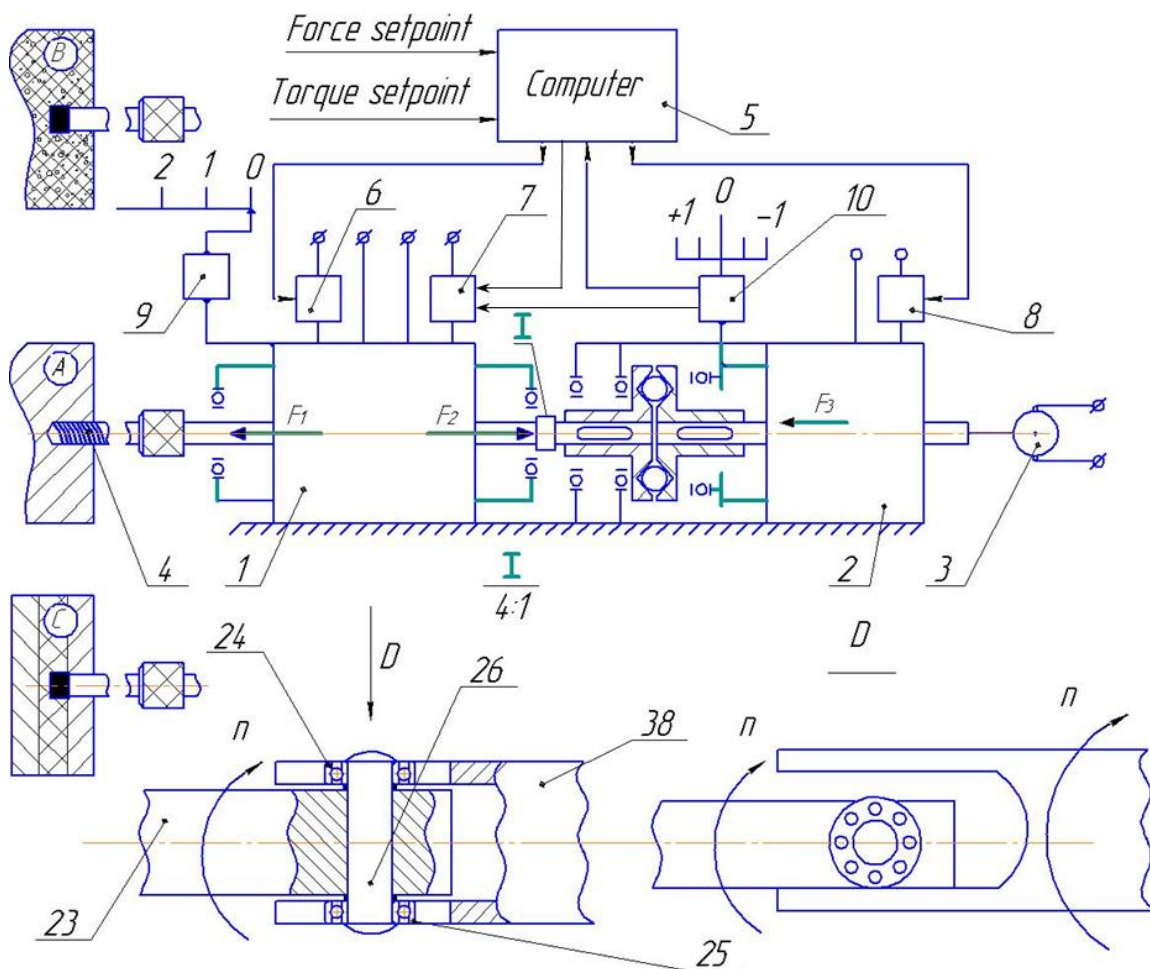


Fig. 8. Principal scheme of the MTS experimental mechatronic head:
A-heat-resistant steel; B-synthegran; C-fiberglass

Source: compiled by the authors

according to the MTS functioning (operation) algorithm (and the control program). Moreover, the force value F_1 is set in such a way that the cutting torque from the action of this force is 5-10 % higher than the torque set on the coupling by force F_3 . This torque corresponds to the zero reading of the sensor 10 linear movements.

In this case, the movable armature 31 of the coupling 2 begins to move. The readings of the sensor 10 are shifted to the “-1” position which is a signal for switching on the unit 7 and the reason for the appearance of force F_2 . The force value F_2 is set to 5-10 % more force F_1 , so the drill bit is removed from the cutting zone. Therefore, the movable coupling half 2 will return to the “+1” position. As a result, the signal of block 7 and the force F_2 disappear. By programmatically varying the values of the forces F_1 and F_2 , it is possible to obtain a variety of algorithms for the MTS functioning according to drilling methods for different materials or their combinations.

This MTS can be attributed to “intelligent machines” that operate according to the well-known principle of the “control configured vehicle” [3] for which speed and maneuverability are priority. Moreover, the technical system created on the principles of the “configurable control device” operates in the mode of mechanical instability. This mode provides high dynamic characteristics of any technical and technological processes due to information and control connections that are integrated with the mechanical units of the system.

The fundamental difference between these kinds of devices is the combination of mechanism self-braking with its absence. Conventional machines, including machine tools, have self-stability due to the use of self-braking friction pairs (screw-nut, gear-rail, etc.) in their kinematic schemes. This allows stopping the working body of the machine in any fixed position, both at working and at idle. This property of the machine provides the necessary coordinate when positioning the working body and the static balance of the tool in space. Moreover, the resistance forces in this space (cutting forces) are not taken into account.

The proposed MTS uses the idea of “contactless mechanisms” in which, by definition, there is no self-braking effect and the working body of the mechanism is held in the desired position by con-

stantly acting on it by oppositely directed forces. These forces provide a non-contact dynamic equilibrium of a solid body in space due to the “checks and balances”.

Thus, the MTS under consideration in the process of performing a drilling operation functions when cutting forces and torques of resistance act on its working body. In such conditions, the actual (unpredictable in advance, floating in time) speed of the tool penetration into the material of the workpiece is automatically formed, regardless of the actual physical and mechanical characteristics of this material. The “driving force” of the cutting process in this case is the load on the cutting tool, i.e. programmable forces from the machine tool and reactive forces from the workpiece. The equilibrium of these forces in accordance with Newton’s third law is the basis for the operation of the sensitive mechatronic mechanism of the “automatic control system by disturbance”, the speed of which is not available for traditional “automatic control system by deviation”.

4.2. Linear electric motor

The linear electric motor 1 (named LM) has a cylindrical housing 11 made of a ferromagnetic material, in which a magnetic circuit 12 is fixed (Fig. 9); it has an excitation winding 13. This winding is powered by a separate adjustable power source 14 which creates a magnetic flux (shown by the arrows in Fig. 8).

Two electric armatures with windings 15 and 16 are located on the LM magnetic circuit. These armatures have the possibility of linear movements along the axis of the magnetic circuit. They are rigidly connected to the body 17 of the drilling head 18, the spindle of which receives rotational motion from the motor 3 (Fig. 8), and reciprocating motion – from the armatures 15 and 16.

The armature windings 19 and 20 receive power from blocks 6 and 7, respectively. Blocks 6 and 7 are powered from DC sources 21 and 22. Block 6 receives a program for changing the current strength from the computer 5. The unit 7 controlled by computer commands 5 additionally responds to signals from the linear motion sensor of the coupling 2

Both windings (19 and 20) are switched on in such a way that when a current passes through them, oppositely directed forces arise which act on the body 17 of the drill head (Fig. 9) and create reciprocating motion to it.

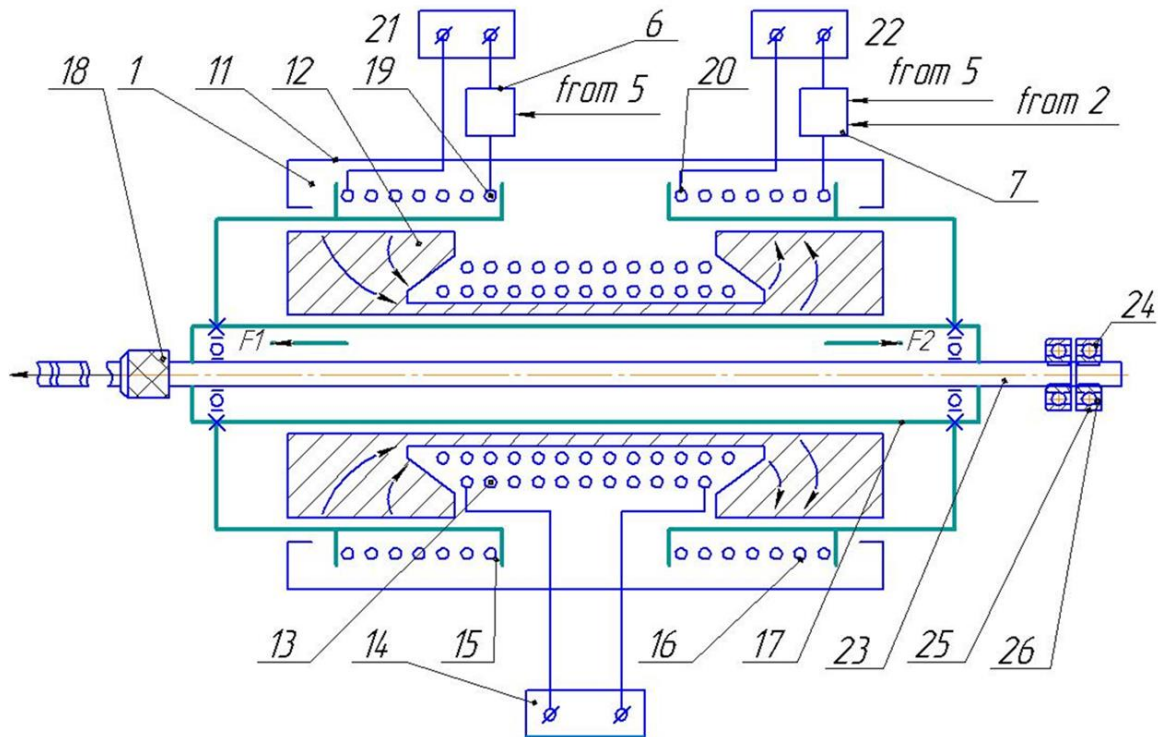


Fig. 9. Principal scheme of the experimental mechatronic head linear motor

Source: compiled by the authors

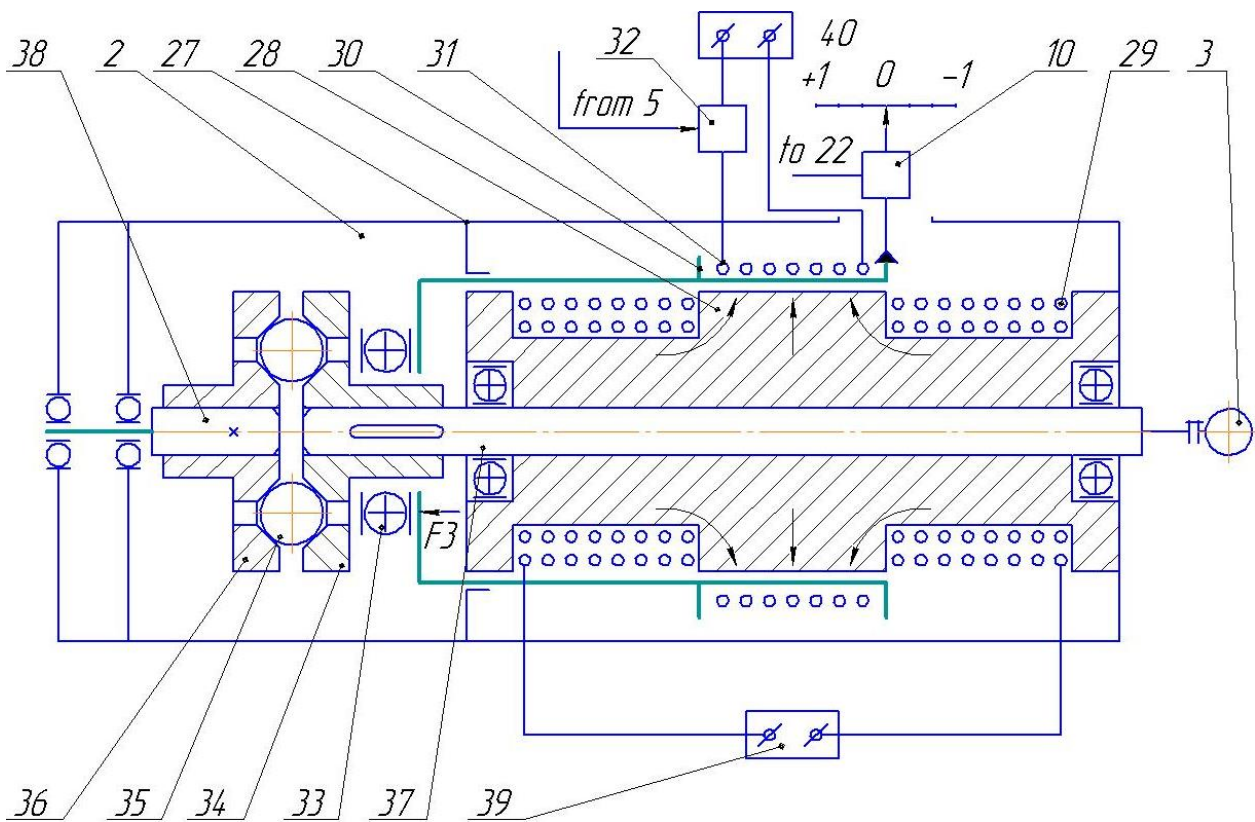


Fig. 10. Principal scheme of the coupling of the experimental mechatronic head

Source: compiled by the authors

The magnitude of these forces (F_1 and F_2) can be determined by the formula (1). Thus, the resulting force of two forces (F_1 and F_2), which act simultaneously on the body of the drilling head, creates to this head a movement in one direction or another in accordance with the computer commands and the algorithm of functioning as a whole.

A device for coupling it with the driven shaft of the coupling 2 is installed on the spindle 23 of the drilling head (Fig. 8, type D). This device is designed to transmit rotational motion to the spindle 23. For this purpose, a shaft 26 is installed at the end of the spindle 23, perpendicularly to its axis (Fig. 8). The spindle 23 axis is bearing two ball bearings 24 and 25. The bearings (24 and 25) are installed in grooves made on the shaft 38 of the driven coupling half (Fig. 10). This connection of the shaft 38 and the drill head spindle allows the spindle to receive rotational movement, and allows the drill head (as a functional unit) to create reciprocating movements.

This design of the LM with two electric armatures which are creating opposite forces allows performing fast-flowing processes during reciprocating movements of solids in space without changing the direction of electric current through the LM windings.

4.3. Electrodynamic coupling

The coupling 2 (Fig. 10) has a ferromagnetic housing 27, inside which there is a magnetic core 28 with a two-section excitation winding 29. The currents flowing in each of the sections of the excitation winding have the opposite direction. Therefore, a magnetic flux is created (shown in Fig. 10 by arrows) which concentrated in the part of the magnetic circuit where the armature 30 with the winding 31 is located. The armature 30 is connected to the linear displacement sensor 10, and the winding 31 receives power from the source 32 which is designed to programmatically change the setpoint current (the strength and shape of this current is set by the computer 5). When a current passes through the armature winding 31, an Ampere's force occurs in this winding in accordance with the formula (2). The armature 30 through the thrust ball bearing 33 presses the movable coupling half 34 through the rolling bodies 35 to the fixed coupling 36.

It should be noted some more special features of the coupling 2 operation (Fig. 8). In the position of the pointer "+1" on the linear displacement sensor

10, there is no signal, and the coupling 2 operates in a mode that is called "stable equilibrium" in engineering. As a result, MTS operates in a stationary mode, the algorithm of which changes only according to the commands of the computer. In the position of the sensor 10 corresponding to the pointer reading "0", the coupling passes to an "unstable equilibrium" depending on the non-deterministic forces that have arisen in the cutting zone and the programmable forces which enter from the drives of MTS linear and rotational movements. In this case, the MTS operation proceeds to intermittent cutting, since the force F_2 is superimposed on the force F_1 . As practice shows, intermittent cutting helps to remove chips from the cutting zone and to increase the machining accuracy in general.

In the position of the pointer "+1" on the sensor 10, the tool is removed from the cutting zone and then performs the specified movements according to the commands of the computer 5.

Finally, the calculation of the torque from the coupling 2 is performed according to the formula (5).

5. CONCLUSIONS

1. A hierarchical automatic control system "by disturbance" has been developed, containing three control levels: the lower (robust automatic control system "by disturbance"), the intermediate (adaptive system with a configurable functioning algorithm) and the upper (intelligent control system corresponding to the stage of technological preparation of production). The system allows setting the necessary cutting forces during drilling and control them based on their technological considerations, including self-tuning of the functioning (operation) algorithm and making adjustments to the control program of the CNC machine.

2. The core of the system is a mechatronic parametric stabilizer of a programmable power load which can work in the tracking mode, with a program change of the setpoint and in the self-learning mode of the mechatronic technological system (MTS). This is a functional assembly unit (machine mechatronic head), which can be assembled and adjusted independently of the technological equipment used.

3. A fundamentally new method of drilling parts made of super-hard and difficult-to-machine materials, for example, deep (up to 30 mm or more)

holes of small diameter (0.1-0.5 mm) with the required drilling quality is proposed and tested on an experimental machine tool. In the course of experimental studies, it was found the following:

- the tool working feed when drilling superhard and artificially created hard-to-machine materials with pronounced anisotropic properties should not be rigidly connected with the tool rotation speed (this condition is usually maintained on CNC machines);

- actual speed of tool penetration into the material (material removal rate) is selected adaptively and with the help of a robust automatic control system based on a combination of the following elements: structure and physical-and-mechanical properties of the workpiece material – cutting ability of the tool – cutting speed and forces – tool wear;

- when machining workpieces made of glass, jade (nephrite), and leuco sapphire, the speeds of tool penetration into the workpiece to be drilled which is obtained in the automatic mode differ tenfold, all other things being equal;

- drilling of workpieces made of glass, jade (nephrite) and leuco sapphire in one package showed that the rates of tool penetration in each of these materials are determined by a ratio of 1:0.3:0.03, i.e. they differ by more than 30 times.

4. The new technology for drilling small-diameter deep holes is an alternative to existing traditional machining technologies, since it involves not only diagnosing the condition of the cutting tool, but also ensuring optimal drilling parameters at different lubricoolant conditions without breaking drill bits and with minimizing their wear, for example, drill bits with a diameter of 0.1-0.5 mm.

5. The created technology of automatically adjustable drilling of small diameter holes can become an alternative to existing drilling (and not only drill-

ing) technology on CNC machines and at the same time an addition to these technologies on the principle of “control in large” (CNC system) and “control in small” (mechatronic load stabilizer) by analogy with the well-known “principle of subordinate regulation”.

6. The functioning (operation) algorithm of the developed MTS is a consequence of the technical requirements of the project, namely, it provides the following possibilities:

- performance (speed) of the automatically adjustable cutting process (the principle of productive machining);

- flexible adjustment of the system for machining new material;

- compatibility with microprocessor and computer equipment;

- modular principle of designing a system containing elements of artificial intelligence (the ability to learn thanks to artificial sensory organs);

- integration of information and energy components in the regulation “by disturbance”;

- ability to generate correctable mathematical models and computer programs for the operation of a mechatronic technological system in real time;

- possibility of remote control of the system and over the local Internet (Internet of things);

- reliability and durability, economic feasibility, environmental cleanliness;

- long-term competitiveness.

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ІНФОРМАЦІЙНЕ ЗАБЕЗПЕЧЕННЯ МЕХАТРОННОЇ ТЕХНОЛОГІЧНОЇ СИСТЕМИ

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АНОТАЦІЯ

У статті акцентується увага на новому способі вирішення проблеми обробки різанням у зв'язку з появою широкої номенклатури надтвердих і важкооброблюваних конструкційних матеріалів для літако-, автомобіле-, корабле- і двигунобудування, а також для космічних апаратів, медицини (ортопедія, стоматологія), атомної та військової техніки. Такі матеріали мають організовану регулярну структуру, високу міцність, супертвердість. Як наслідок, виникає проблема бездефектної обробки цих матеріалів без пошкодження їх врівноваженої структури. У статті описаний новий підхід і сформульовані інноваційні принципи створення нового класу мехатронних технологічних систем для прецизійної обробки деталей із зазначених матеріалів на прикладі операції свердління глибоких отворів малого діаметра. Ядром мехатронної технологічної системи є мехатронний параметричний стабілізатор силового навантаження на ріжучий інструмент. Мехатронна технологічна система забезпечує програмне завдання, автоматичну стабілізацію і підтримку в стежить режимі силового навантаження на

ріжучий інструмент з управлінням “по збуренню”. Наприклад, в технологічному циклі свердління отворів малого діаметра така система оберігає свердла від поломки. Запропонована інтегрована технологічна система, що містить наступні три рівні управління: інтелектуальний (верхній), адаптивний (середній) і робастний (нижній). Основу багаторівневої системи становить швидкодіюча робастна система автоматичного управління “по збуренню”. Збуренням є момент навантаження, який або автоматично стабілізується, або відстежується при завданні програми від комп'ютера, або змінюється за програмою, що задає алгоритм функціонування для мехатронної технологічної системи. Цей алгоритм може змінюватися в широких межах при різних способах обробки деталей різанням, включаючи формоутворення довільних 3D поверхонь по їх цифровим моделям. Мехатронна технологічна система, яка запропонована, легко вбудовується в технологічну систему верстатів з ЧПК, розширюючи їх можливості шляхом переведення штатної керуючої програми ЧПК на більш високий рівень ієрархії керування. Це дозволяє обробляти будь-які складнопрофільні деталі, включаючи деталі “подвійної кривизни” (імпелери, турбінні лопатки, гребні гвинти і т.п.).

Ключові слова: Мехатронна система; інформаційне забезпечення; лінійний електродвигун; електродинамічна муфта; свердління отворів; складнопрофільна поверхня; бездефектна обробка

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