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CREATION OF AUTOMATIC CLAMPING MECHANISMS FOR SPINDLE ASSEMBLIES OF MACHINE TOOLS USING A FORMALIZED DESCRIPTION OF STRUCTURAL ELEMENTS

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The characteristics of the functioning of automatic mechanisms for clamping workpieces and cylindrical tools in the spindle assemblies of metalworking machines determine the potential for improving the productivity and quality of processing. The conducted research is aimed at developing new approaches to the creation of automatic clamping mechanisms with qualitatively new and necessary characteristics of their functioning. The formation of new characteristics is achieved by implementing appropriate changes at the structural level of an object. The results obtained provide better opportunities for the development of structures of automatic clamping mechanisms by improving the systematization of a review of an increased number of alternative options for their structural elements. This was achieved by solving the problem of formal description and representation of structural elements operating on the basis of various physical effects within one subject area of the systematization matrix. The results allow strengthening the heuristic potential in the design and involving an extended range of physical effects suitable for effective energy transfer and conversion in the operating conditions of automatic clamping mechanisms. The possibility of describing structural elements as digital codes helps to increase the efficiency of analysis and processing of information of the initial design stages. Using the codes of the selected structural elements, three sequences corresponding to the structures of automatic clamping mechanisms according to the brief descriptions [1.7–2.4]–(1.1–2.3); [1.7–2.6]–(1.1–2.3); [1.7–2.6+1.6/1.7–2.1]–(1.1–2.3) were compiled. On their basis, designs of automatic clamping mechanisms with predictably better characteristics and extended technological capabilities are developed

Keywords: clamping mechanism drive, clamping chuck, spindle, clamping forces, mechanism structure

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1. Introduction

Automatic mechanisms for clamping workpieces and cylindrical tools in the spindle assemblies of metalworking machines determine the potential for increasing the productivity and quality of processing. Automatic clamping mechanisms (ACM) are a subsystem of spindle assemblies (SA) of machine tools and affect their operating characteristics. Improving the productivity and quality of processing by increasing the cutting speed requires increasing the maximum spindle speed and, as a result, improving its dynamic characteristics. An increase in the volume of material removed from the workpiece in one pass of the tool increases the magnitude of their force interaction. This, in turn, requires an increase in the clamping forces of the workpiece and the tool.

The ACM structure consists of two main subsystems – the drive and the clamping chuck. The ACM drive is the largest subsystem and determines the power and basic design characteristics, while the clamping chuck directly affects the workpiece positioning accuracy. The power characteristics of ACM determine the maximum values of clamping force and limit the maximum values of the torque that can be transmitted to the workpiece. The design features of the ACM determine the possibility of high-precision balancing of the SA and its dynamic characteristics and, as a result, limit its maximum speeds. There are also a number of additional requirements for ACM, which also affect processing efficiency. They relate to ensuring the stability of the workpiece fixation parameters regardless of external disturbing factors, such as deviations of the nominal characteristics of the workpiece, changes in spindle speed, instability of the power supply characteristics, etc.

In modern production, the requirement of clamping workpieces with different characteristics of materials and design, in particular, thin-walled ones, while ensuring the reliability of fixation and the absence of plastic deformations due to clamping forces, is relevant. Thus, the requirements for ACM are also related to the need for effective control, expansion of the range of clamping objects, the absence of disturbing effects on other machine systems, etc.

The constant development of modern power drives of machine tools, metalworking tools and cooling and lubrication systems of the cutting zone create new potential opportunities for improving cutting modes. The development of ACM designs with the necessary improved characteristics helps to better meet the above requirements and use potential opportunities to improve the productivity and quality of processing. This gives reason to claim that scientific research aimed at developing opportunities to ensure new necessary characteristics of ACM is relevant. The practical implementation of the results of such research provides new opportunities for the development of the theory of designing and creating ACM, which contribute to increasing the productivity and quality of processing on metalworking machines.

2. Literature review and problem statement

The vast majority of scientific works on ACM are devoted to the possibilities of improving the operating characteristics of individual ACM components, in particular, clamping chucks. For example, in [1], the impact of the design of clamping chucks on the characteristics of the machining process in the context of sustainable production was investigated, but no approaches were proposed for improving their characteristics. In [2], the kinematic characteristics of the designs of object clamping mechanisms in form-closure technological equipment were considered. At the same time, there are no studies on the possibility of expanding their functional capabilities. In [3], modeling and research of specific operating characteristics of the spindle assembly were carried out, in particular, taking into account the action of inertia and clamping forces. The work does not offer approaches to achieve better performance characteristics. The results of studying the connection of the device for fixing the tool and the spindle, taking into account the influence of centrifugal forces and clamping forces, are highlighted in [4], but alternative structures of the mechanism for eliminating additional stresses in the connection weren't presented. In [5], an analysis of the operation of automatic clamping mechanisms as part of a spindle assembly with proposing methods for compensating the action of centrifugal forces was carried out. At the same time, no conceptual approaches have been given to eliminate the influence of high speeds. A study of the characteristics of collet chucks taking into account the influence of centrifugal forces of inertia was conducted in [6]. This paper also does not provide methods to achieve better clamping conditions under the action of centrifugal forces of inertia. In [7], the operation of the workpiece clamping mechanism with an input rotating link at the gap sampling stage was simulated, but no solutions were offered regarding the possibilities of improving the operation of the mechanism of this type. Approaches to determining the optimal clamping force are presented [8] in order to ensure reliable fixation and the absence of deformations of the workpiece and elements of the clamping chuck. At the same time, the work does not propose new methods of clamping force control. In [9], a system for measuring clamping force in a three-jaw clamping chuck was developed in order to effectively control its value. These studies do not contain new solutions to improve the efficiency of clamping process control. There are studies [10] that simulated the magnitude of clamping forces of workpieces in order to ensure the absence of their deformations and high-quality processing. The results obtained do not reflect information about the necessary changes in the design of the clamping mechanism. The paper [11] presents a study of the design shortcomings of the lathe chuck actuated by a hydraulic drive. At the same time, no new approaches aimed at changing the functioning characteristics have been proposed. In [12], a simple and practical method of measuring the clamping forces of cylindrical workpieces on lathes is proposed, which allows determining the optimal clamping forces in the absence of deformations and slipping of the workpiece during processing. This work does not specify the possibility of using the obtained results to improve the operation characteristics of the clamping mechanism. In [13], certain aspects of the advantages and expediency of using mechatronic systems for the construction of metalworking machines based on the modular principle and the possibility of their interaction with other production processes are considered. In particular, mechatronic systems for effective reduction of certain types of errors and damping of vibrations are demonstrated. In [14], the dynamic characteristics of the clamping mechanism operation are considered. In [15], new possibilities of fastening the workpiece surface using the physical effect of cooling are described, but no ways to implement this method for different groups of machine tools are proposed. The study [16] indicated the need to identify the operation features of the clamping mechanism, taking into account the influence of external loads on the clamping cam chuck.

In general, available research is aimed at improving individual characteristics of ACM subsystems by partially changing the design or geometric or mass parameters of their elements while preserving the general operation principles and structure of the mechanism. This approach allows making effective changes in the quantitative characteristics of the ACM functioning. According to the general design theory, one of the main causes of the problem is the fundamental impossibility to achieve qualitatively new functioning characteristics of the object by making changes only at the design level. At the same time, among the existing studies, no approaches were found that ensure qualitatively new characteristics of ACM. This allows us to assert the expediency of research on the development of new approaches and methods of ACM design ensuring qualitatively new and necessary functioning characteristics.

3. The aim and objectives of the study

The aim of the study is to develop approaches to the creation of ACM, which make it possible to obtain qualitatively new and necessary characteristics of their functioning.

To achieve the aim, the following objectives were set:

– to develop a method of systematized presentation of structural elements of ACM functioning on the basis of various physical effects within one subject area;

– to determine the principles of forming a description of ACM structures as a sequence of digital codes;

– to determine the sequence of the ACM creation process based on the proposed approaches and developed structures.

4. Materials and methods

The object of research is the functioning characteristics of ACM as a subsystem of SA. The subject of research is the possibility of forming qualitatively new and necessary characteristics of ACM, which allow improving the cutting modes and expanding the technological capabilities of the machine. According to the main research hypothesis, the formation of qualitatively new necessary characteristics of ACM is achieved by introducing appropriate changes at the structural level. The structure of ACM determines the sequence and characteristics of converting the input energy into the potential energy of the stressed state of the clamped object. The structure of a particular ACM can be described by a set of structural elements and relationships between them. When selecting structural elements, it is assumed that the characteristics of their main inputs and outputs are fully known. At the same time, simplifications related to the generalization of the impact of the characteristics of collateral inputs and outputs of structural elements on the ACM properties are accepted.

Analysis of ACM design methods indicates that the existing methodology has long preserved traditional approaches and mostly involves the use of one type of energy converter, for example, mechanical (Fig. 1, *a*, 2) or hydraulic (Fig. 1, *b*) to create clamping forces. Typical structures of clamping chucks provide for the application of axial force through the drawbar rod from the ACM drive and its transformation into clamping force through mechanical amplifying elements. In particular, the most common is the use of cam (Fig. 1, *a*) and collet (Fig. 1, *b*) clamping chucks as part of ACM.

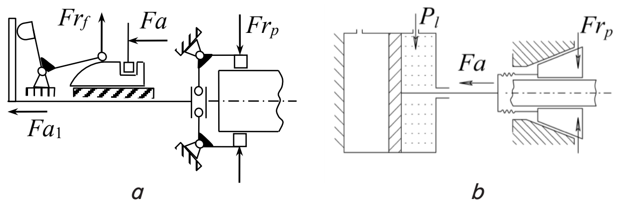

Fig. 1. Operating diagrams of typical automatic clamping mechanisms containing: *a* — form-closure mechanical drive and lever clamping chuck; *b* — hydraulic drive with powering retention of the position of the output link and collet clamping chuck

The existing types of ACM have a number of shortcomings, the elimination of which opens up opportunities for increasing the efficiency of modern metalworking machines. Typical ACM structures with geometric closure of the clamped state (Fig. 1, *a*, 2) are built on the basis of mechanical systems. At the same time, the blocking of the output link from movement in the reverse direction after completion of the clamping process is ensured due to the shape of the mechanism link. The movement of the input link with conical and cylindrical surfaces under the influence of the input force *Fa* causes the appearance of a radial force Fr_f on the arm of the lever, which leads to the appearance of a larger axial force Fa_1 on its other arm. The force Fa_1 is transmitted through the drawbar in the form of a pipe passing through the spindle to the chuck. The possibility of using a drawbar in the form of a pipe allows using long rods fed through the spindle as workpieces. When using a lever clamping chuck (Fig. 1, *a*), the force Fa_1 is applied to the large arms of the chuck levers, which causes the radial clamping force Fr_p to appear on the smaller arms of the levers. In the final part of the movement of the input link, the point of its contact with the lever arm shifts from the conical surface to the cylindrical one. This makes it impossible for the reverse movement of the input link to occur due to the forces of interaction with the lever in the absence of the force *Fa*. ACM of this type (form-closure) have high indicators of energy efficiency and operational safety, as they ensure the retention of the workpiece without supplying energy from the outside. This helps to securely hold the workpiece during processing, even in the case of emergency power loss or deviation of its parameters from nominal values. One of the critical disadvantages of form-closure ACM is the constant value of movement of the clamping elements, which corresponds to the adjustment to a certain nominal size. This leads to uncontrolled changes in the operating parameters of the mechanism in the case of clamping workpieces with a significant deviation of the actual diametrical size from the values for which the ACM is configured. Namely, this reduces the possibilities of high-quality fixation of cheaper workpieces with a significant deviation of the diametric size from the nominal values, such as a hot-rolled bar. The supply of mechanical energy to ACM of this type involves the force interaction of the spindle with other subsystems of the machine, which leads to the appearance of shock loads and is a potential cause of offsets in the SA elements and excitation of vibrations. The presence of ACM elements with the ability to move in the radial direction causes the influence of centrifugal forces of inertia on their operating characteristics when increasing the SA speed. This also complicates the implementation and maintenance of high-precision balancing of the SA because it is very difficult to ensure completely symmetrical positioning of the radially moving elements at every moment of time, especially when clearances appear due to wear. So, the listed shortcomings of ACM of this type have a negative effect on the accuracy and speed characteristics of SA.

ACM drives with retention of the clamped state with energy consumption are usually created on the basis of hydraulic systems (Fig. 1, *b*). The input energy in the form of the pressure of the working fluid P_l is supplied through a movable connection to the hydraulic cylinder, on the rod of which an axial force *Fa* appears, which is transmitted to the clamping chuck. In the collet chuck, the axial force *Fa* is transmitted to the collet petals, where, through the conical surface, it is transformed into radial clamping forces Fr_p. ACM hydraulic drives provide a wide range of settings for clamping forces and working stroke of the output links, which allows high-quality fixation of workpieces of various designs and sizes.

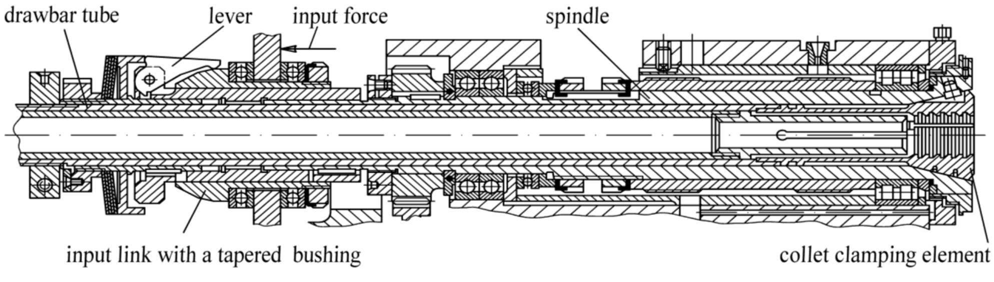

Fig. 2. Automatic clamping mechanism of a typical structure with form closure and collet clamping chuck as part of the spindle assembly of the automatic lathe

Their disadvantages are the need for constant power supply (even while holding the workpiece) from hydraulic subsystems of machine tools by supplying the working fluid through a movable connection to the rotating spindle, in particular, at high speeds. This reduces the reliability and efficiency of fixing the workpiece and complicates the design of the machine tool. Furthermore, ACM with retention of the output link (clamping elements) with energy consumption can be built on the basis of mechanical systems, but such designs are used much less often and have a number of disadvantages.

When searching for elements for ACM structures, any quantitative calculations have an approximate, evaluative nature. The description of the ACM structure is formed by a sequence of descriptions of each of the structural elements in the form of codes corresponding to the characteristics of the inputs and outputs of each structural element in accordance with the accepted systematization matrix. The function of each structural element can be implemented using one or more physical effects in different design options. For example, the transmission of axial force can be carried out with the help of a mechanical bar or hydraulic system, and the torque – by a gear, frictional forces, or electromagnetic interaction. The selection of physical effects and options of their technical implementation for creating a structural element is carried out according to the principle of better compliance with the requirements for its functioning. The combination of a significant number of characteristics of mechanical, electrical, and hydraulic energy converters creates problems that are also associated with reducing the number of options to suitable and better ones for constructing a particular ACM.

In the most general form, the set of requirements (Fig. 3) put forward for each of the structural elements (N_0–N_k) can be represented as two sets (W_0–W_k) and (w_1–w_k). The requirements (W_0– W_k) are determined by the conditions for the efficiency of the functions of a certain structural element, and can be partially determined from the decomposition of the requirements for the operation of the designed ACM. Examples of requirements are: operation at high speeds, the need to hold the workpiece without supplying energy from the outside, stability of the clamping force with the deviation of the workpiece size from nominal values, etc. The requirements (w_1–w_k) (Fig. 3) are determined from the conditions of interaction with neighboring structural elements and, therefore, are formed according to the characteristics of the outputs of the previous structural element $N_{k\text{-}1}$. In the presence of several alternative physical effects n_{k1}–n_{ki}, which make it possible to implement the functions of a certain structural element N_k, there is a need to choose the best alternative in accordance with the conditions for meeting the requirements (w_1–w_k) and (W_0– W_k).

Preliminary selection of physical effects for the construction of a certain structural element can be carried out by the two most important criteria using the principle of selecting a set of Pareto-optimal alternatives. A graphic representation of the process of preliminary selection of structural elements is shown in Fig. 4, where the direction of the axes corresponds to the direction of increasing values of criteria q and m, i.e. increasing certain advantages. The efficiency of functioning at high speeds (under the influence of centrifugal forces) and the effect of the structure on the possibility of reducing the mass and improving the balancing quality of ACM were chosen as the criteria for selecting an alternative option for constructing a certain structural element. The values of the criteria are determined by the rating principle. At the first stage of selection, «outsider» objects are discarded from the total set. These include the objects located in the areas selected by the coordinates of the objects, the value of at least one of which is the largest. In this case, outsider objects n_1–n_4 fall into the region according to the coordinates of objects n_5 and n_k (Fig. 4), and objects n_6–n_8 are the best competing options for further selection by pairwise comparison.

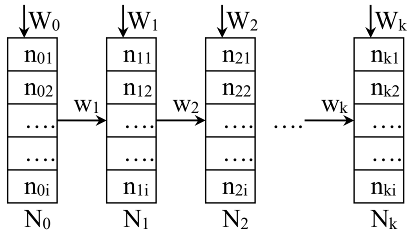

Fig. 3. General order of selecting options for structural elements of automatic clamping mechanisms

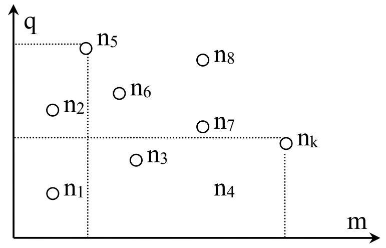

Fig. 4. Preliminary selection of the set of the best alternatives of the structural elements of automatic clamping mechanisms by two criteria

Based on the analysis of the operation features of energy converters in the operating conditions of ACM, conclusions were made regarding the influence of individual types on the mechanism functioning. Supplying input energy through electromagnetic interaction avoids a number of disadvantages compared to mechanical and hydraulic systems. This helps to reduce the likelihood of shock pulses, oscillations, and uncontrolled displacements of SA elements, as well as negative effects associated with surface friction and losses of working fluid in moving joints. This improves the conditions of creating ACM for SA with increased accuracy, speed, and reliability characteristics. This is confirmed by the trend of the rapid spread of motor-spindle designs where the spindle torque is also supplied by electromagnetic interaction. Unlike hydraulic and pneumatic, the power supply of electric ACM does not require the use of special bulky systems and expands the possibilities of using analog-digital control systems of ACM. The use of hydraulic systems to change energy characteristics makes it possible to arbitrarily direct input and output forces and transmit them over large distances without significantly increasing the weight and complexity of the structure. The use of hydraulic and electrical systems helps to reduce mechanical transmission links such as rods and shafts, which are not involved in the change of energy characteristics and increase the mass and complexity of the structure. Such features of hydraulic systems also allow meeting the requirements of axial symmetry of the mass arrangement, limiting the weight and radial dimensions of the unit. Mechanical converters in ACM function as actuators of clamping chucks, where the input axial force is converted into radial forces on the clamping elements.

5. Results of studying the methods of conducting initial stages of development of automatic clamping mechanisms

5. 1. Method of system presentation of structural elements of clamping mechanisms within one subject area

In order to improve the methods of ACM development, a new approach is proposed, involving the selection of structural elements that function on the basis of an expanded range of physical effects atypical to these mechanisms and are systematized in one matrix. Systematization of the structural elements of ACM is based on representing them as cause-and-effect relationships between the characteristics of their inputs and outputs (Fig. 5). The main characteristics of the inputs and outputs of structural elements that determine their functional purpose can be implemented by several physical effects.

Representation of structural elements with different principles of functioning within one system expands the heuristic possibilities for developing new ACM structures. The systematization matrix provides the designer with a more complete and systematic consideration of an enlarged array of alternative options for structural elements where their functions are provided by a certain physical effect. Based on the proposed systematics, it is possible to formally record the structures of existing ACM, including with the aim of developing improved analogs using alternative structural elements that provide the necessary functions and have improved characteristics.

In the left column of the systematization matrix (Fig. 5), there are physical quantities describing the inputs of structural elements, and in the upper row – outputs. The cell at the intersection of a certain row and a column indicates a structural element that ensures the transformation of input (causal) values into output (effect) values due to a certain physical effect. In order to simplify the demonstration, the presented fragment of the systematization matrix (Fig. 5) includes a description of the input and output characteristics of certain types of energy converters for ACM structures. Their list can be expanded by including torques around radially directed axes, elastic forces and applying chemical transformation energy and thermal energy, which are used much less often in special fixation mechanisms.

Considering the requirement for axial symmetry of the ACM's layout, it is preferable to use the reference to the ACM's axis of symmetry, which is the axis of its rotation, for the convenience of describing the characteristics of their structural elements. In the presented systematization (Fig. 5), symbols are accepted for the characteristics of the inputs and outputs of the structural elements provided by certain physical effects. In particular, the following designations are made: Fa – force axial, Fr_f – force radial centrifugal, Fr_p – force radial centripetal, Ta – torque axial, P_l – pressure of liquid, Ce – electric current, M_f – magnetic field. The characteristics of the values presented in the systematization can be displayed with different degrees of detail in accordance with the tasks of a certain design stage. For example, the method of action of the magnetic field M_f can be additionally distinguished by direction – M_{fa} and M_{fT}, respectively, axial and tangential (circulation on circumference). Also, the type of electric current (Ce_D and Ce_A, respectively, direct and alternating current) and the direction of pressure between the plunger and the working fluid of the hydraulic system (P_{lR} and P_{lA}, respectively, radial and axial direction) can be described in detail.

No.	No.out.	2.1	2.2	2.3	2.4	2.5	2.6	2.7
No.inp.	Out. Inp.	$Fa \longrightarrow$	Fr_f - -↑- -	Fr_p - -↓- -	Ta -↷-	P_l ↓↓↓	Ce ⌀∽⌀	M_f ⇅⇅⇅
1.1	$Fa \longrightarrow$	1.1–2.1	1.1–2.2	1.1–2.3	1.1–2.4	1.1–2.5	1.1–2.6	1.1–2.7
1.2	Fr_f - -↑- -	1.2–2.1	1.2–2.2	1.2–2.3	1.2–2.4	1.2–2.5	1.2–2.6	1.2–2.7
1.3	Fr_p - -↓- -	1.3–2.1	1.3–2.2	1.3–2.3	1.3–2.4	1.3–2.5	1.3–2.6	1.3–2.7
1.4	Ta -↷-	1.4–2.1	1.4–2.2	1.4–2.3	1.4–2.4	1.4–2.5	1.4–2.6	1.4–2.7
1.5	P_l ↓↓↓	1.5–2.1	1.5–2.2	1.5–2.3	1.5–2.4	1.5–2.5	1.5–2.6	1.5–2.7
1.6	Ce ⌀∽⌀	1.6–2.1	1.6–2.2	1.6–2.3	1.6–2.4	1.6–2.5	1.6–2.6	1.6–2.7
1.7	M_f ⇅⇅⇅	1.7–2.1	1.7–2.2	1.7–2.3	1.7–2.4	1.7–2.5	1.7–2.6	1.7–2.7

Fig. 5. Fragment of the matrix of systematized representation of the structural elements of automatic clamping mechanisms

The review of the options for the formation of the radial clamping force presented in the systematization (Fig. 5) revealed the possibility of using the structure with the input pressure of the working fluid according to the code (1.5–2.3), which is currently not used. An option with the input rotational force according to the code (1.4–2.3), used in typical hand-operated chuck structures was also identified. The typical structure of the ACM clamping chuck involves the use of an axial input force to create radial clamping forces according to the code (1.1–2.3). The use of this typical structure simplifies the use of standard clamping elements in the design of clamping chucks. This makes it possible to calculate the parameters of the clamping process using standardized values of the parameters of clamping elements, such as weight and shape, area and roughness of their surfaces. Options for the transmission of input energy were identified from the systematization matrix (Fig. 5) in accordance with the above considerations regarding the expediency of using certain types of converters in ACM structures. In particular, it is advisable to supply energy due to the effect of electromagnetic interaction in accordance with the codes [1.7–2.4], [1.7–2.6], [1.7–2.1].

5. 2. Principles of forming a description of the structures of automatic clamping mechanisms as a sequence of digital codes

Using the proposed approach, the development of ACM structures for spindle assemblies of machine tools was carried out. In accordance with the presented conditions for combining elements to build structures, in particular, the compatibility of their inputs and outputs (Fig. 4), the condition for combining their codes is formulated. The condition determines that the second digit of the element code matches the last digit of the previous one's code. To highlight the codes of the input links, they are presented in square brackets, and the codes of all other elements are in round ones. When applying the input link, which provides the transmission of power supply to the ACM by means of electromagnetic interaction according to the code [1.7–2.4], the next link can be selected among the elements with the first part of the code 1.4. The need to convert the torque obtained on the input link into an axial force on the input link of the clamping chuck indicates an option of the code of the next element (1.4–2.1). Further transformations of the energy characteristics involve increasing the magnitude of the received axial force and transmitting it from the drive to the clamping chuck. Taking into account the features of hydraulic systems as part of ACM presented in the work, it is advisable to apply the element according to the code (1.1–2.5). To form a sequence of this element with the selected standard structure of the clamping chuck according to the code (1.1–2.3) by the rules of combining element codes, it is necessary to use (1.5–2.1). The resulting new structure of ACM is described by the following sequence of codes:

[1.7–2.4] (1.4–2.1) (1.1–2.5) (1.5–2.1) (1.1–2.3). (1)

For short description and conditional classification of the structures described by codes, it is proposed to use the codes of their input and output links. Therefore, a short description of (1) is [1.7–2.4]–(1.1–2.3).

The selected option of the input energy of ACM according to the code [1.7–2.6] is the basis for the operation of electric generators and transformers. If the codes are combined in the structure of the mechanism for this case, the code of the next element is selected from the list of those containing 1.6 in the first part. Further energy conversion involves obtaining an axial force according to the code (1.6–2.1) to actuate the clamping chuck of the pre-selected standard structure (1.1–2.3), while the need for a significant increase in its value is obvious. As a rule, compact mechanical transmissions of the wedge and lever types increase the output forces when their directions are changed. To ensure a significant increase in the axial force in conditions of limited dimensions, it is advisable to use a series connection of a pair of converters of mechanical energy characteristics of the type (1.1–2.2) and (1.2–2.1). Thus, the description of the ACM structure is as follows:

[1.7–2.6] (1.6–2.1) (1.1–2.2) (1.2–2.1) (1.1–2.3). (2)

A short description of (2) is [1.7–2.6]–(1.1–2.3).

Supplying energy to power the ACM using the effect of electromagnetic interaction makes it possible to obtain several types of energy at the output of the input link. This indicates the possibility of using a complex input link in ACM. The structural element pre-selected as a promising option for energy supply according to the code [1.7–2.1] is applied in combination with the option according to the code [1.7–2.6], which was also involved in constructing the previous structure. Thus, the code of the structural element with a combined input link is [1.7–2.6+1.6/1.7–2.1]. The axial force obtained at this input link of the ACM requires significant amplification and transmission to the front end of the spindle through its internal space to feed the input of the clamping chuck of a typical structure (1.1–2.3). Similarly to the previous case, to increase the axial force while preserving its direction, it is advisable to use a pair of series-connected mechanical converters according to the codes (1.1–2.3)·(1.3–2.1). Taking into account the advantages of using hydraulic systems for energy transmission and conversion in the ACM presented in the work, it is advisable to use the converter (1.1–2.5) located in the ACM drive and the converter (1.5–2.1) located in the front part of the SA to supply the axial force to the clamping chuck with a structure according to the code (1.1–2.3). The code description of the new structure is as follows:

[1.7–2.6+1.6/1.7–2.1]·(1.1–2.3),

(1.3–2.1)·(1.1–2.5)·(1.5–2.1)·(1.1–2.3). (3)

A short description of the structure (3) is [1.7–2.6+ +1.6/1.7–2.1]–(1.1–2.3).

5. 3. Sequence of development of clamping mechanisms based on the structures described in the form of codes

Based on the developed ACM structures (1)–(3), the next design stage was carried out, related to the construction of their block diagrams (Fig. 6) as part of the SA (SA is highlighted with a dashed line). In all block diagrams, the external part of the energy supply system is fed with current *Ce* to create a magnetic field M_f with certain characteristics. In the block diagram (Fig. 6, *a*), developed in accordance with (1), hydraulic energy converters are used to increase the axial force *Fa* to the value Fa_1 and transfer it to the clamping chuck. That is, unlike traditional schemes, mechanical traction is not used. The block diagram (Fig. 6, *b*), built according to (2), contains an electrical system that is also used for more efficient energy transfer in the form of electrical energy Ce_1 from the drive to the clamping chuck.

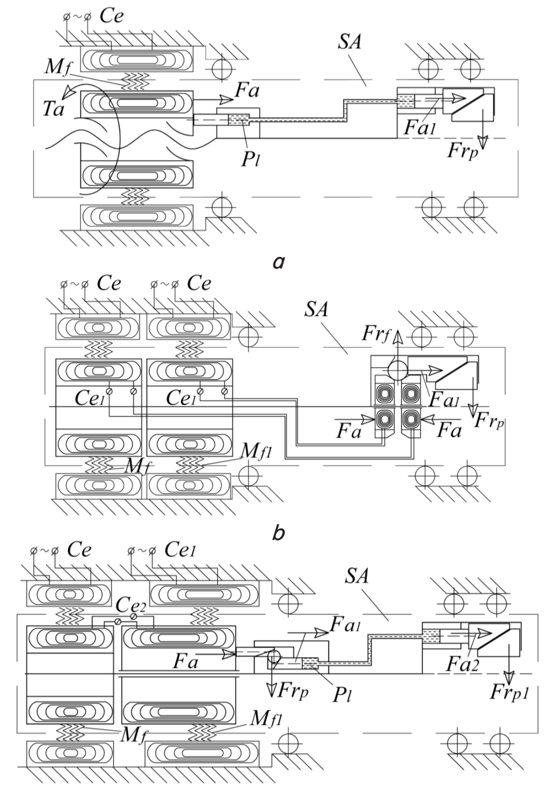

Fig. 6. Block diagrams according to the codes:
a – [1.7–2.4]–(1.1–2.3); *b* – [1.7–2.6]–(1.1–2.3);
c – [1.7–2.6+1.6/1.7–2.1]–(1.1–2.3)

The block diagram developed in accordance with (3) (Fig. 6, *c*) contains a combined input link that expands the control capabilities of the ACM. For example, changes in the characteristics of the electric current Ce_2 in the input circuit according to the algorithms programmed in the controller and the signals of sensors about the ACM parameters create prerequisites for the development of a system for automatic adjustment of characteristics.

The design of ACM (Fig. 7) according to the structure (1) is presented as part of a modern version of the SA – a spindle motor unit, which includes spindle 1 on supports 2. The drive of this SA includes rotor 3 and its stator 5 on the body of machine 4 with the possibility of their electromagnetic interaction. The axial force generated on nut 6 during its rotation is transmitted through thrust bearing 8 to plungers 9 of small diameter *d*, located coaxially in fixed distributor sleeve 10, which is clamped on the conical surface of spindle 1 by nut 11. The cylindrical object of fixation 13 is clamped in collet 14, attached through a threaded surface to spindle 1. Collet 14 also has the possibility of force interaction with the conical surface of sleeve 15, which interacts with the plunger of a larger diameter *D*. Sleeve 15 is spring-loaded by spring 17 relative to flange 18, rigidly connected to spindle 1.

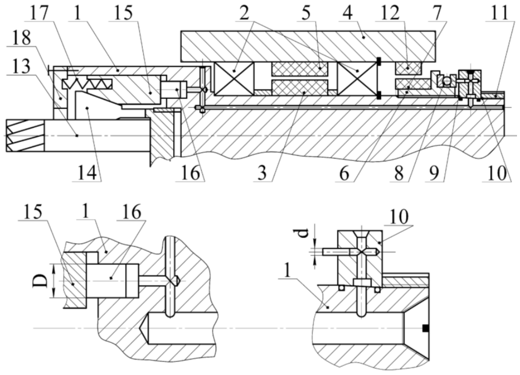

Fig. 7. Automatic clamping mechanisms as part of the motor spindle of the machine according to the structure (1)

Connecting the windings of stator 12 to the power source causes the appearance of an electromagnetic field, which affects the windings of rotor 7. As a result, a torque occurs on rotor 7, which is transmitted to nut 6. This leads to the movement of nut 6 along the thread of spindle 1. In the closed hydraulic system, the pressure resulting from the effect of axial force on the plungers of small diameter *d* is transmitted to output plungers 16 having a larger diameter *D*. Thus, a greater axial force acting on the collet occurs.

The ACM design according to the structure (2) is presented as part of the SA (Fig. 8) where spindle 1 is located on supports 2 and 3, which are based on the brackets of body 4. The functioning of the mechanism begins when current is supplied to windings 8 and 9 of stator 7 through electrical connectors 18 and 19, respectively. Current is supplied to the windings of electromagnets 10 and 11 through the conductors connected by connectors 20 and 21, respectively. Due to the influence of the electromagnetic field of windings 8, 9 on windings 5, 6, there is a supply current of electromagnets 10 and 11 and their force interaction, which causes the convergence of bushings 12 and 13. At the same time, bushings 12 and 13 interact with balls 16 and make them move in the radial direction from the axis of rotation. The interaction of balls 16 with the conical surface of spindle 1 causes the ball to move together with sleeve 13 in the axial direction to the left. The conical surface of sleeve 13 has the possibility of force interaction with the conical surface «*b*» of the petals of collet 15, which leads to their convergence and clamping of the fixation object. Flange 17 is rigidly attached to the end of spindle 1, with which spring 14 can interact to return sleeve 13 to its initial position, which corresponds to the process of unclamping the fixation object.

The design of the ACM as part of the SA is developed according to the structure (3) and is presented as part of the spindle assembly (Fig. 9, 10) where axially movable armature 2 with electromagnets 3 is located on spindle 1. To clamp cylindrical object 18 (Fig. 9), an electric current is alternately supplied to connectors 6 of electromagnets 5.

As a result, an electromagnetic field is alternately formed around electromagnets 5, which interacts with one of the nearest electromagnets 3 of anchor 2 and causes the appearance of an axial effort. When current is supplied to connectors 10 in the stator windings of generator 8, a magnetic field arises under the action of which a current is generated in generator rotor 7, which feeds electromagnets 3. From electromagnets 3, the axial force is transmitted to anchor 2 and causes its axial movement relative to stator 4 and spindle 1 to the left. Due to the interaction of the shaped surface of anchor 2, located at an angle to the axis of rotation (Fig. 9, 10), with ball 11, its radial movement and force interaction with the shaped surface of plunger 12 occur. This causes the axial movement of plunger 12 and, as a result, compression spring 13 and the movement of some working fluid 14 through the channels of the closed hydraulic system into the chamber of the plunger of a larger diameter 15. As a result, plunger 15 is pushed out of its working chamber and the force is transferred to sleeve 16, which causes it to move to the right, deform spring 19 and interact with the conical surface of collet 17.

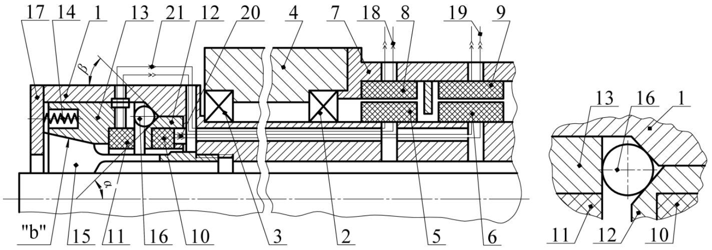

Fig. 8. Automatic clamping mechanisms as a part of the spindle assembly of the machine according to the structure (2)

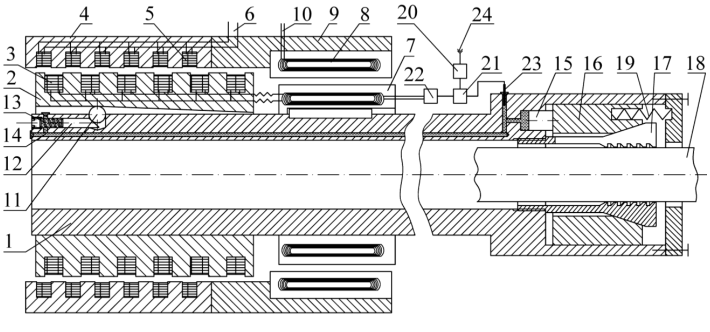

Fig. 9. Automatic clamping mechanisms as part of the spindle assembly of the machine according to the structure (3)

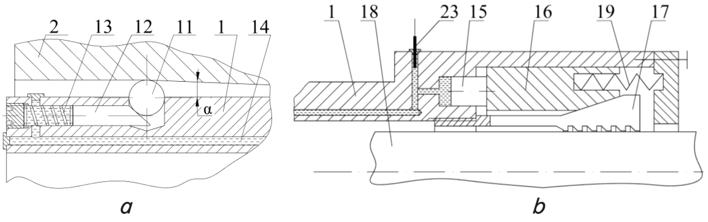

Fig. 10. Fragments of the automatic clamping mechanisms design: *a* – wedge mechanism with a hydraulic system plunger; *b* – fragment of the collet chuck driven by a hydraulic system plunger

The force interaction of sleeve 16 with collet 17 causes the movement of its clamping elements, which ensures the clamping of fixation object 18. The value of the angle α (Fig. 10, *a*) is smaller than the angle of friction in the contact between ball 11 and anchor 2, which keeps anchor 2 from moving under the action of the force from ball 11. This provides self-braking and fixation of the position of anchor 2 relative to spindle 1 after the clamping process is completed. Thus, it is possible to hold fixation object 18 without the consumption of electricity by electromagnets 3 and 5 or with a significant reduction of it, which can be used to increase the reliability of holding the position of anchor 2.

The magnitude of the clamping force of fixation object 18 is determined by the magnitude of the mechanical stress of the mechanism elements, which is reflected in the magnitude of the pressure of working fluid 14 in the hydraulic system. This provides a feedback signal for the control system. Pressure sensor 23 (Fig. 9, 10) is installed in the hydraulic system near the chamber of larger diameter plunger 15. Before the clamping process, the value of the control signal J_i from the control device is transmitted through connector 24 to memory device 20 (Fig. 9) and is recorded at its lower level. The control system also contains data comparison device 21 and relay element 22 with a logical output. After the start of the clamping process, the value of J_i is rewritten in storage device 20 from the lower level to the upper level and is transmitted to comparison device 21, where it is compared with the value of the signal J_s from hydraulic sensor 23. At the same time, comparison device 21 determines the result using the dependence $\Delta J_c = J_s - J_i$. The result of the calculation in comparison device 21 ΔJ_c is transmitted to relay element 22 with a logical output and a non-linear static characteristic of the function $\Delta J_c, J = f(\Delta J_c)$. The result J takes discrete values of 0 or 1 in cases where $\Delta J_c < \tau$ and $\Delta J_c \geq \tau$. The value of τ is the minimum value of the response signal of relay element 22. The value of τ is set in accordance with the determined value of the clamping force tolerance. This determines the operation of the ACM control system regarding the algorithm for switching on windings 3 and 5 of the ACM electric drive. The clamping process ends when the state $\Delta J_c < \tau$ is reached.

6. Discussion of the results of research on the design of clamping mechanisms using a formalized description of structures

Improvement of the conditions for ACM development was achieved by solving the problem of formal description and representing structural elements functioning on the basis of various physical effects within one subject area of the systematization matrix (Fig. 5). To improve the efficiency of analysis and processing of design information, a method of describing structural elements as digital codes is proposed. According to the presented conditions (Fig. 4) for combining elements into an ACM structure, in particular, the compatibility of their inputs and outputs, the condition for building and describing ACM structures as a sequence of digital codes is formulated. Using the codes of the selected elements, three sequences corresponding to the structures with the concise descriptions [1.7–2.4]–(1.1–2.3); [1.7–2.6]–(1.1–2.3); [1.7–2.6+1.6/1.7–2.1]–(1.1–2.3) were compiled. Based on the digital descriptions of the structures, the corresponding block diagrams (Fig. 6) and designs (Fig. 7–10) of ACM were developed.

In most of the known studies, in particular [7, 14, 16], the improvement of the characteristics of the clamping mechanism is ensured by making changes at the level of designing nodes and optimizing the geometric and mass parameters of their elements. This approach provides for the preservation of the mechanism structure and allows improving the quantitative characteristics of its functioning. In contrast to these approaches, this work presents the results that allow changing the quality characteristics of ACM by implementing changes at the level of the object structure. As a result, the proposed approach makes it possible to create ACM with the necessary qualitatively new performance characteristics for given operating conditions or expand technological capabilities. Unlike the studies [1, 3, 6] aimed at identifying the relationship between the design features of clamping cartridges and the influence of centrifugal forces on the efficiency of clamping, this work suggests considering other aspects as well. In particular, for the same purpose, the work takes into account the suitability of the functioning of energy converters in the ACM drive for operation at high speeds. In contrast to [9–11], where the assessment of the influence of clamping mechanisms on the processing characteristics is carried out only through the quality of fixation, this work proposes to expand the assessment indicators. In particular, it is proposed to take into account the features of ACM by the characteristics of their influence on the balancing conditions of the SA in order to increase the maximum speed values. In typical ACM structures, the power supply is carried out by transmitting the axial force (Fig. 1, *a*, 2) or working fluid pressure (Fig. 1, *b*) from special subsystems of the machine. This causes the appearance of friction of the contacting surfaces, leaks of the working fluid in moving joints, disturbing effects in the form of shock pulses, uncontrolled displacements of the SA elements, a decrease in its balance level, etc. To eliminate these problems from the systematization matrix, alternative options for supplying power to ACM were identified. A non-contact option using the physical effect of electromagnetic interaction according to the codes [1.7–2.1], [1.7–2.4] and [1.7–2.6] was chosen, which has a number of advantages.

The resulting solutions provide better opportunities and conditions for developing the ACM structure by improving the systematization of the review of an increased number of alternative options for structural elements. So, this allows strengthening the heuristic potential in the design and involving an extended range of physical effects suitable for energy transfer and conversion in the operation conditions of ACM. The use of atypical physical effects was demonstrated in the development of new ACM structures (1)–(3) in order to increase the efficiency of individual stages of input energy conversion into the potential energy of the stressed state of a clamped object. The obtained AMS have predictably better characteristics of operation at high speeds and clamping force control, which contributes to improving cutting modes and expanding the range of fixation objects.

Limitations of the presented research are related to objective difficulties in determining and modeling the characteristics of inputs and outputs of structural elements. That is, there is a problem of insufficient determination of the input and output characteristics of certain structural elements. This limits the use of the proposed approaches to structural elements with incompletely known characteristics and reduces the ability to predict the ACM characteristics. The disadvantage of the study is the lack of consideration of the impact of secondary (non-essential, not determining the main function) inputs and outputs of structural elements on the formation of the ACM structure. According to general estimates, the influence of side inputs and outputs can most affect the quantitative characteristics of the ACM functioning.

The next logical stage of the presented research can be the development of the elements of the proposed structures (Fig. 7–10), related to the determination of their parameters and evaluation of the power and energy characteristics of new ACM. It is also planned to carry out a more detailed development of special control systems similar to the proposed one (Fig. 9), which will improve the technological capabilities of ACM. The proposed method of describing structural elements as digital codes creates prerequisites for further development of methods for automating initial design stages.

7. Conclusions

1. A solution to the problem of formal description and representation of the structural elements of ACM functioning on the basis of various physical effects within one subject area of the systematization matrix is proposed. This method of representation allows increasing the range of characteristics and the number of options of structural elements that can be considered as alternatives during the development of the structure. The resulting solution provides better opportunities and conditions for the development of ACM structures by increasing the efficiency of the review and selection of their structural elements from an increased number of alternative options, which also contributes to increasing the heuristic potential of the development process.

2. To improve the efficiency of analysis and processing of design information, the method of describing structural elements as digital codes is proposed. In accordance with the presented conditions for combining elements into the ACM structure, in particular, the compatibility of their inputs and outputs, the condition for building and describing the ACM structures as a sequence of digital codes is formulated. Using the codes of the selected elements, three sequences corresponding to the structures with the brief descriptions [1.7–2.4]–(1.1–2.3); [1.7–2.6]–(1.1–2.3); [1.7–2.6+1.6/1.7–2.1]–(1.1–2.3) were compiled. The description in the form of digital codes also creates prerequisites for further development of methods for automating initial design stages.

3. The proposed approach to the selection of structural elements in order to build their sequence, which determines the ACM structure, creates improved conditions for making necessary changes at the level of mechanism structures. This expands the possibilities of obtaining qualitatively new necessary characteristics of ACM structures. Based on the obtained sequences of structural elements, ACM designs have been developed, which have predictably better characteristics of operation at high speeds and clamping force control. This creates prerequisites for increasing cutting modes and expanding the range of fixation objects.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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