Improvement of the Automatic Workpiece Clamping Mechanism of Lathes to Expand Technological Capabilities

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Abstract. The force characteristics of actuators of automatic clamping mechanisms determine the forces of clamping workpieces in the spindle assemblies of lathes. It determines the opportunities for clamping the workpieces with a wide range of material characteristics and construction rigidity. The conducted work aims to develop a new method of measurement of the force characteristics of the drive of automatic clamping mechanisms. The measurement issue is solved by implementing the contactless method, which meets the requirements for ensuring the efficient operation of a high-speed spindle assembly. The developed structure provides new opportunities for creating a control system with better possibilities for interactive estimation of the clamping forces. The use of the developed design helps to increase the quality of clamping and, consequently, the productivity of machining workpieces with an expanded range of characteristics. The proposed design of the clamp drive does not contain radially movable parts and implements a contactless power supply. It is proposed to control the clamping mechanism by non-contact measurement of the torque at the input link of the mechanical drive in the range of 0–50 N·m.

Keywords: Clamping Forces · Clamp Drive · Spindle · Contactless Measurement · Product Innovation

1 Introduction

Modern manufacturing demands that machinery for mechanical processing, particularly its most common form, the turning one, be more technologically flexible. This results from the ongoing technological advancements in mechanical engineering, including the increase in the variety of materials and workpiece structures, particularly thin-walled ones. Modern cutting tools' characteristics and methods for cooling the cutting zone enable a greater variety of processing modes, which is required to improve productivity and quality. One of the conditions for increasing the cutting modes is the sufficiency of the clamping forces on the workpiece, which ensure its retention from displacement under the action of cutting forces. At the same time, the magnitude of the clamping forces should not exceed values that lead to plastic or significant elastic deformations of the workpiece. Also, the forces for clamping a workpiece should not be excessive, as

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this reduces the reliability and work resources of the mechanism and increases energy consumption.

The automatic workpiece clamping mechanism is part of the spindle unit of the machine and consists of two main subsystems—the drive and the clamping chuck. The force characteristics of the drive clamping mechanism (DCM) determine the magnitude of the clamping forces.

Research related to the development of automatic control of DCM power characteristics is essential as it contributes to solving the problems of increasing the efficiency of automatic control of the clamping mechanism and, in particular, the magnitude of the clamping forces. The results of such research are helpful for the practical field of metalworking machine construction, as they create prerequisites for developing clamp mechanism designs with improved technological characteristics. Improving methods of controlling the force characteristics of clamping mechanisms contributes to a complete use of the potential capabilities of the machine for processing an expanded range of materials and constructions of workpieces (particularly thin-walled ones), which explains the relevance of this work.

2 Literature Review

Most existing scientific studies related to clamping mechanisms are devoted to analyzing the issues of increasing their force and kinematics characteristics. The report [1] analyzes the drawbacks of the hydraulically operated lathe chuck's design. At the same time, no fresh strategies have been put forth to alter the control method of force characteristics. Studies [2] have simulated the clamping forces that workpieces would experience to ensure that there would be no deformations. The acquired results do not provide information on the adjustments that must be made to the clamping mechanism's design. The functioning of the workpiece clamping mechanism with an input rotating link at the gap sampling stage was simulated in [3], but no recommendations were made regarding how to make this sort of mechanism operate more efficiently. The impact of clamping chuck design on the features of the machining process, particularly in the context of sustainable production, was examined in [4], but no methods for enhancing these characteristics were suggested. The dynamic features of the clamping mechanism's operation are considered in [5]. In the article [6], new options for securing the workpiece surface utilizing the cooling effect are explained, but no suggestions are made for applying this technique to various machine tools. At work [7], modeling and studying the special properties of the spindle unit's operation were done, including accounting for the effects of inertia and clamping forces. The work does not provide strategies for improving performance parameters. Functional analysis of the spindle unit's automatic clamping mechanisms and a suggestion for a method for compensating for the impact of inertial forces were made in [8]. At the same time, no theoretical strategies to counteract the impact of high rotational frequencies have been put forth. The kinematic properties of clamping mechanism structures for object fixation in technological equipment with the provision of geometric locking were considered in the study [9]. The possibility of enhancing their functional capacities has not yet been studied. The findings of investigations into the connection between the tool-fixing device and the spindle, which took clamping and centrifugal forces into account, are noted in [10]. But design decisions for the mechanism for removing the extra stress in the connection weren't considered. The properties of collet chucks were the subject of research [11]. Additionally, this paper does not suggest any techniques for improving clamping conditions by improving clamping drives. There are methods for figuring out the ideal clamping force offered [12] to guarantee accurate fixing and the absence of deformations of the workpiece and clamping chuck components. However, the findings do not suggest new ways to regulate the strength of the clamping forces. In order to properly manage clamping force value, a system for measuring it in a three-jaw clamping chuck was created in work [13]. This research offers no novel approaches that could potentially boost clamping process control effectiveness. The advantages and expediency of employing mechatronic systems for the modular principle-based building of metalworking machines and the potential for their connection with other production processes are some topics covered in the work [14]. Mechatronic systems are effective at controlling forces and reducing certain types of faults. According to research [15], it is essential to determine the characteristics of the clamping mechanism's operation while considering the impact of external loads on the cams of clamping chucks. [16] proposes a straightforward and helpful method for measuring the clamping forces of cylindrical workpieces on lathes that calculate the ideal clamping forces without workpiece deformations and sliding during processing. This work does not mention utilizing the findings to enhance the clamping mechanism's operational qualities.

At the same time, no information was found about researching the possibilities of contactless measuring and controlling the power characteristics of the clamp mechanism drives to provide feedback for the control system of the clamp mechanism. All of this makes it possible to assert the feasibility of conducting a study devoted to developing the structure and design scheme of automatic clamping mechanism drives, allowing for interactive control of their power characteristics and, as a result, control of the amount of clamping forces.

3 Research Methodology

The purpose of the work is to develop the drive structure of the clamp mechanism, which provides the possibility of automatic interactive control of the power characteristics of its operation. This will make it possible to improve the quality of fixation of a broader range of workpieces with different physical and mechanical characteristics of the material and structural rigidity properties, particularly thin-walled ones. The object of the study is the transformation of the input energy of the drive of the clamping mechanism into the strained state's potential energy of the clamped fixation object. The subject of the study is determining the transmission characteristics and transformation of forces during the operation of the clamp mechanism drive. The central hypothesis of the work considers the possibility of automatic determination of the force characteristics of the clamping mechanism drive in real-time (interactive) for automatic control of the clamping forces of a workpiece. There are assumptions in the study that, when building the structure of the clamping mechanism, the characteristics of its structural elements' main inputs and outputs are fully known. Simplifications adopted in the study are that developing the structure of the clamping mechanism as a subsystem of the spindle assembly, the main characteristics of the spindle as the basic element of the spindle assembly are common to various types of lathes.

Four typical types of structures (Fig. 1) that differ in specific fundamental operating characteristics were discovered due to the analysis of the structural components of automatic clamping mechanisms. Each of these types also has common disadvantages that limit the possibilities or effectiveness of their use for particular operating conditions.

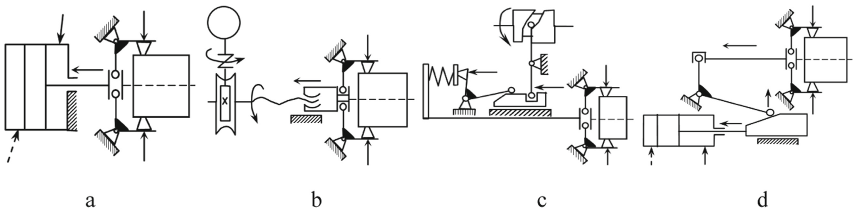

Fig. 1. The main types of structures of automatic clamping mechanisms: a – hydraulic and pneumatic; b – mechanical with self-braking; c – mechanical with self-locking; d – hydraulic with self-locking

The following can be singled out as general shortcomings in the functioning of existing designs of automatic workpiece clamping mechanisms: centrifugal forces of radially movable (solid or liquid) elements affect the operation efficiency; using outer mechanisms for preparing and supplying input energy and a large number of energy converters needed to create clamping forces leads to additional energy losses, reduced reliability and control efficiency; design deteriorates the dynamic characteristics of a spindle assembly; high probability of losses of the working fluid when supplied to the rotating spindle and others.

According to the general assessment [3, 5], structures that ensure self-fixation (geometric locking or self-braking) in the state when the workpiece is clamped are promising. This makes it possible to use many advantages related to the reliability of holding the workpiece, the clamping mechanism's energy efficiency, and the machine design's simplification. In the case of applying geometric locking, a constant, defined amount of movement of the clamping elements is ensured. As a result, it ensures that the nominal value of the clamping force is achieved only for workpieces with nominal values of diametrical dimensions. Using the most common, less expensive, uncalibrated workpieces with significant radial dimension deviation leads to instability of the clamping force value and, as a result, the quality of fixation. Implementing the self-braking effect in the clamping mechanism's elements allows for achieving and maintaining the required value of clamping forces at various clamping surface diameter dimensions.

In order to reduce the probability of appearance and the magnitude of the influence of disturbing external factors when building DCM for high-speed spindle assemblies with increased accuracy, it is appropriate to avoid the mechanical interaction of its elements with the external subsystems of machines. This explains the expediency of using clamping mechanism drives with input energy supply through the electromagnetic interaction of the stator and rotor and the implementation of self-braking to maintain the system's tense state during workpiece processing. Expanding the technological capabilities of the equipment requires ensuring automatic control of the amount of clamping forces. This determines the possibilities of high-quality fixation of workpieces with different characteristics of materials and stiffness of structures, as well as the maximum values of the force interaction of the workpiece with the tool, that is, the maximum cutting modes. Control of DCM performance characteristics requires the determination of the torque developed on the rotor of its electric motor (EM). To fulfil the condition of avoiding mechanical impact on the DCM elements, the torque must be measured by a contactless method. The magnetoelastic effect (effect Villari) is the basis for one of the most used non-contact ways of measuring torque.

A structure schematic (Fig. 2) of the clamping mechanism comprising DCM with non-contact measuring of the torque value from EM is suggested according to the factors discussed above. Both the advantages of using mechatronic systems as a component of technical equipment and the methods for designing their structures for efficient use are taken into account [14]. The measuring unit (MU) incorporates a sensor that reacts to the degree of deformation of the deformable element and operates based on the magnetoelastic effect. Electrical signals from the MU as feedback are transmitted to the control system (CS), which regulates the magnitude of the EM torque in accordance with the specified needs. The self-braking converter (SBC), which generates axial force for the clamping chuck (CCh), receives the torque. The SBC also ensures that the clamping mechanism system maintains a stressed state after completing the clamping process. CCh creates radial forces for clamping a workpiece.

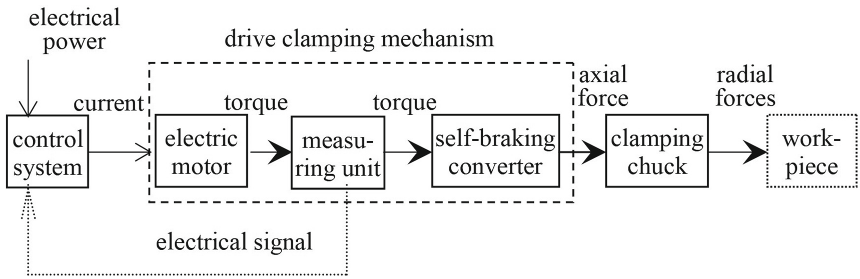

Fig. 2. Block diagram of clamping mechanism with the proposed drive.

4 Results and Discussion

According to the block diagram (Fig. 2), the schematic design of the DCM is created (Figs. 3, 4).

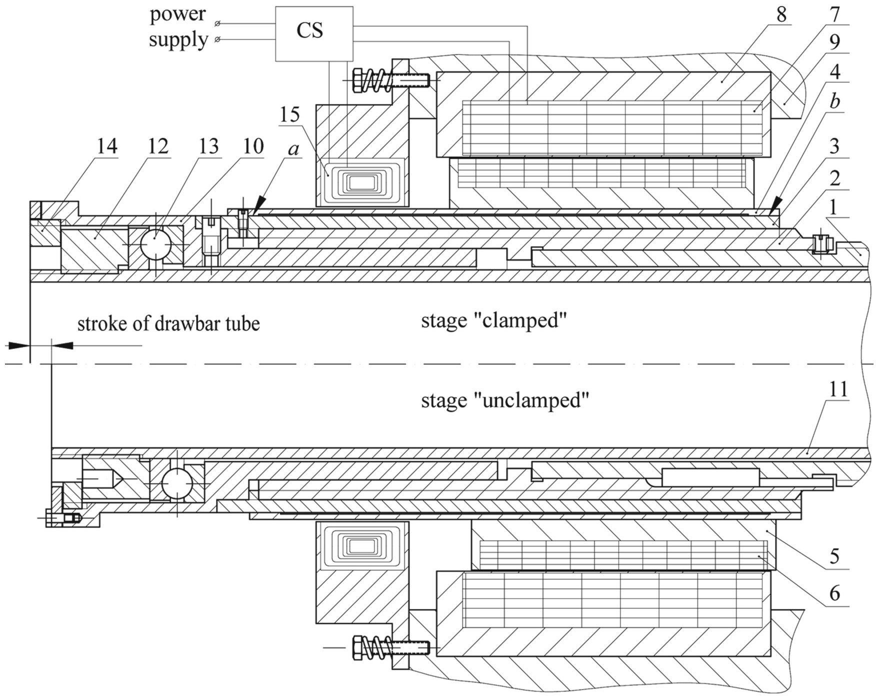

Fig. 3. Construction diagram of the drive of the clamping mechanism assembly.

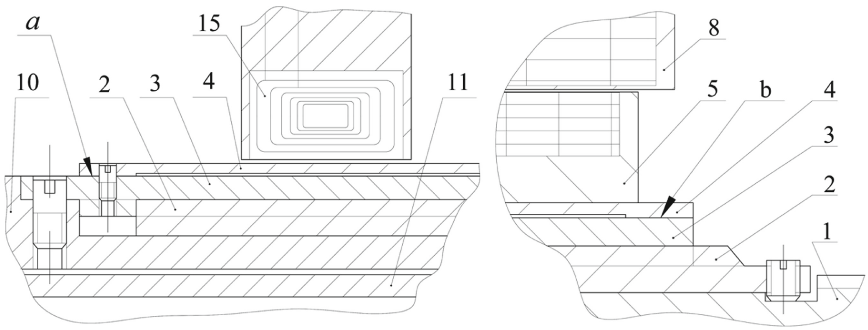

Fig. 4. Fragments of the drive of the clamping mechanism with locations of the fixed "a" and movable "b" support surfaces of the deformable element.

On the exterior surface of spindle 1 (Figs. 3, 4), which has a running thread with a rectangular thread profile and polished surfaces, bushing 2 is attached. A bushing 3 containing a corresponding internal thread surface is screwed onto the threaded surface of bushing 2, and the relative positioning of the bushings is based on the outer cylindrical surface of the thread of bushing 2. A deformable element in the form of cylinder 4 is located on bushing 3 and can contact bushing 3 through two support surfaces "a" and "b". At the same time, surface "a" is fixed on the outer surface of bushing 3 immovably (landing with tension-type H7/n6), and surface “b” is fixed with the possibility of joint movement but without a gap (landing sliding type H7/js6). Rotor 5, which is part of the motor of the clamping mechanism, is immovably fixed on cylinder 4. The electric windings 6 located on rotor 5 have the possibility of electromagnetic interaction with electric windings 7 of stator 8, which is fixed immovably on machine body 9. Cartridge 10 can transmit the axial force to the clamping collet chuck (not shown in the figure) through a rod in the form of pipe 11, nut 12 screwed onto it, and thrust bearing 13. Nut 12 is located in the inner cylindrical space of cartridge 10 and also has the possibility of force interaction with internal nut 14, which is screwed into cartridge 10. The part of the surface of cylinder 4 (Fig. 4) located between its support surfaces “a” and “b” may be electromagnetically interacted with by a magnetoelastic effect sensor 15 attached to machine body 9.

The drive of the proposed design works as follows. Power is delivered from the control system CS to the stator’s windings 7 to perform clamping (Fig. 3). The magnetic field of windings 7 with windings 6 creates a torque on rotor 5, which is transmitted to bushing 3 through cylinder 4. The rotation of bushing 3 (relative to bushing 2) leads to their mutual axial movement. The axial force of bushing 3 is transmitted to cartridge 10 through thrust bearing 13 located in its inner space. The thrust bearing 13 transmits the axial force to rod 11 through nut 12 screwed onto it. The magnitude of this axial force determines the magnitude of the clamping force and depends on the magnitude of the torque generated on rotor 5. The torque of rotor 5 (Fig. 3, 4) is transmitted through cylinder 4 to bushing 3. Simultaneously, under the influence of the torque of rotor 5, the deformation of cylinder 4 occurs between its support surfaces “a” and “b”. It is proportional to the magnitude of the torque and is registered by the non-contact sensor of magnetoelastic effect 15. Signals from sensor 15 are transmitted to control system 16, which determines the characteristics of the power supply current of windings 7 of stator 8 in accordance with the specified equipment operation requirements. After the end of the clamping process, the supply of current to windings 7 is stopped. Therefore, the clamping force is maintained due to self-braking in the threaded connection of bushings 2 and 3. To perform the unclamping, the current is supplied to windings 7 with characteristics that cause the movement of rotor 5 in the opposite direction compared to the clamping process. The workpiece is unclamped under the action of the elastic deformation forces of the collet chuck petals (not shown in the drawing).

A variant of using the developed drive in the automatic clamping mechanism with a collet chuck as part of the spindle unit is proposed (Fig. 5). The design predictably has improved characteristics. The absence of radially movable elements aids in achieving and maintaining high balancing accuracy, which contributes to high rotation frequencies. The absence of mechanical contacts between the elements of the clamping mechanism and its power supply and control systems reduces the likelihood of disturbing effects on the operation of the spindle unit. The ability to maintain the clamped state without supplying energy (by self-braking) contributes to increasing the safety and reliability of the mechanism in cases of uncontrolled power loss. Because the proposed DCM is powered by electricity, the possibilities for modernizing existing spindle assemblies are expanded because it does not require the replacement of its external mechanical or hydraulic power systems.

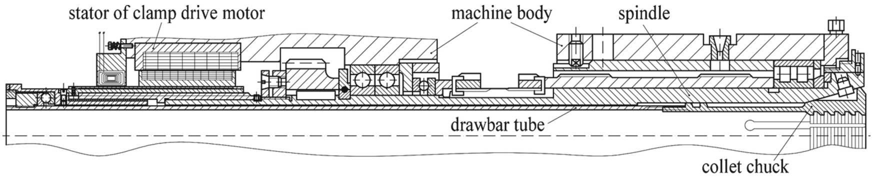

Fig. 5. The automatic clamping mechanism with the proposed drive and collet chuck as a part of the spindle unit of the lathe.

The maximum-sufficient value of the axial force is supplied from a clamping drive through the drawbar tube 11 (Figs. 3, 4, 5) to the input of the collet chuck (Fig. 5) for the effective clamping of a rod workpiece, is accepted $S = 15$ kN. The tangential force that must be applied to the threaded part of the bushing 3 (Fig. 3, 4) with a median diameter d to obtain the corresponding value of the axial force S on the drawbar tube 11 (Figs. 3, 4, 5) is determined by $F_T = S \cdot tg(\alpha + \varphi_J)$. For the diameter of the threaded connection bushings 2 and 3, $d = 85$ mm, and the pitch of the thread $p = 2$ mm, the angle of the rise of the thread $\alpha = 0.43°$, and the angle of friction takes $\varphi_J = 4°$. The value of the torque from the action F_T is $T = 0.5d \cdot F_T$. Thus, $T = 0.5 \cdot 0.085 \cdot 15000 \cdot tg\ 4.43° = 49.4$ Nm, which is within the maximum values of torque (in overload mode) that can be provided by modern electric motors for a short time. The use of the electric motor's maximum loaded modes of operation is acceptable in this case. This is due to the short operation time (only during the process of clamping a workpiece—0.5–2 s) with a subsequent relatively long period of forced cooling, provided by the spindle rotation during the processing of the workpiece. With the selected thread pitch, a large margin ($\varphi_J >> \alpha$) of self-braking in the threaded connection is provided, which is necessary to prevent unscrewing (unclamping of a workpiece) in the event of alternating dynamic loads, vibrations, and the appearance of radial elastic deformations. As a non-contact sensor of magnetoelastic effect 15 (Figs. 3, 4) can be used with existing variants of torsiometers with a wide range of diameters (60–860 mm) and shaft speeds (0–10,000 rpm) from ABB b.v. Marine & Cranes Torductor®, ASEA (Sweden), and others. The interactive contactless control of the power characteristics of the clamp drive provides new opportunities to improve the quality of fixing workpieces of reduced strength. In particular, those made of structurally heterogeneous materials and, for example, obtained by powder metallurgy methods [17].

5 Conclusions

A technical solution to the engineering task of measuring the power characteristics of the clamping mechanism drive in real-time (interactively) and considering the operating conditions of the high-precision spindle assembly is proposed. The problem is solved by introducing an element for non-contact measurement into the structure. The absence of mechanical contact reduces the probability of the appearance of external disturbing influences and violations of the established position of the spindle assembly. The ability to interactively measure the power characteristics of the clamping mechanism drive creates prerequisites for further development of a clamping mechanism control system with feedback and improved capabilities for automatic control of the workpiece clamping forces. Measuring and controlling the torque on the input link of the clamping drive in the range of 0–50 Nm makes it possible to obtain the range of output forces. That is necessary for clamping rod workpieces with an expanded spectrum of physical and mechanical characteristics of materials and characteristics of structural stiffness, in particular thin-walled ones. Further research is devoted to developing the structure of the clamping mechanisms' control system elements with the actuator's proposed design and feedback.

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