# A Control Configured Mechatronic Mechanism

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**Abstract.** The design features of a mechatronic mechanism (MM) configured by the control were given. MM provides automatic control of the torque on the shaft by adjusting the pressing force of the working body to the object to be machined, for example, the force of pressing the cutting tool to the workpiece. The MM relevance, for example, in motor-spindles of CNC machines was determined by the need to improve (based on a new machining technology paradigm) the technology for machining parts from modern superhard and difficult-to-machine materials, as well as materials with pronounced anisotropic properties (materials with coatings, reinforced fibrous materials), precious stones, and porous materials. Design of a MM sensitive element was developed for an automatic control system "by disturbance" and based on a ball-bearing screw converter with the necessary range of linear movement of the working body of the technological machine. The developed MM mathematical model connects its geometric and electromagnetic parameters and shows the influence of the helical groove angle in the ball-bearing screw converter on the force of pressing a cutting tool to the machining workpiece. It made it possible to develop recommendations on the value of the helical groove angle for implementing various technological machining modes in nano-, micro-, and macro-technologies conditions.

**Keywords:** Product Innovation · Machining Technology · Electromagnetic Force · Electrodynamic Force · Action and Counteraction · Pressing Force · Torque Control

## 1 Introduction

The increasing volume of creation of competitive technology in industrial production involves using new structural materials with improved physical and mechanical properties or a strictly organized structure. Examples of such materials are numerous. These are artificially grown crystals with a hardness that is commensurate with the hardness of the machining (e.g., cutting) tool working part. These are polymer composite materials with solid inclusions adjacent to a soft polymer component. These are aluminum alloys with increased adhesion to the cutting tool. New materials require a significant novelty


V. Tonkonogyi et al. (Eds.): InterPartner 2023, LNME, pp. 72–81, 2024.
https://doi.org/10.1007/978-3-031-42778-7_7

in approaches to their mechanical machining technology. An equally important aspect is the technological problems of high-quality machining of materials with a pronounced anisotropy of properties throughout their volume. A representative of this kind of material is, for example, syntegran (synthetic granite). It contains solid inclusions and a binder component – synthetic resins. These resins have high adhesion not only to solid fractions but also to the cutting tool. This is especially evident at elevated cutting temperatures, as it leads to various machining defects if it is performed without temperature control based on cutting force and torque control.

The above materials are difficult to process with high quality because, for example, it is difficult to maintain the required trajectory of the drill due to the possible withdrawal of its axis from a given direction. The reason is the occurrence of uneven lateral forces when the geometric dimensions of the voids of the material being processed are commensurate with the dimensions of the cutting part of the machining tool.

Opportunities for quality machining are provided by a mechatronic technological system based on a mechatronic mechanism (MM), which allows at the initial stage providing the required force parameters of machining (for example, cutting force and torque) and at the final stage of machining – the necessary accuracy. Such MM can perform its functions only due to the joint action of the programmable forces (from the MM control system) and the oppositely directed forces from the external environment [1]. These two forces (action and reaction) "configure" MM; give it the very ability to function. The conventional machines (designed not on the control configured MM concept) have inherent self-stability in their designs. Therefore, they can operate in the self-braking mode (due to the action of friction forces) and have a static transfer function. In the case of control-configured MM, however, there is a structurally inherent mechanical instability of MM. Without an automatic control system and environmental resistance, such MM will not work [2]. The specified mechanical instability often turns out to be necessary to ensure the MM required dynamic characteristics, with an instantaneous change in loads on the machining tool. MM developed in the paper is connected with creating and practically implementing a new paradigm in machining the above materials, for example, on CNC machines.

The paper aims to develop a control-configured mechanism, i.e., configured by control, to provide kinematic (displacement, speed, acceleration) and power (cutting force and torque) machining parameters, for example, on CNC machines. The object of research is modern mechatronic and intelligent technological machines, for example, CNC machines. The subject of research is MM, which is configured by automatic control.

## 2 Literature Review

This paper proposes a new technology-oriented approach, the basics of which have been described previously with two [1] and one [3] control windings. The ball-bearing screw converter described below is part of MM, designed and implemented based on the well-known concept of a control-configured vehicle or, in other words, a vehicle configured by control [4]. The set of control operations forms a control process. By analogy, a set of work operations forms a work (physical) process. Automatic devices can also partially or entirely perform control operations [5]. However, nothing is said here on the control configured vehicle concept.

The literature notes that the control-configured vehicle concept can be achieved through intelligent control [6] and full intelligent automation [7].

Implementing the control-configured vehicle concept in systems operating in the multilevel control mode is most effective in adaptive [8] and intelligent [9] technological machines. Therefore, it is necessary to rely on the well-known provisions in this area: hierarchical control [10] and intelligent machining systems [11]. At the same time, the principle of hierarchical (multilevel) control makes it possible to optimize the ratio between the control ranges of power parameters for systems of the upper and lower levels of control, on the one hand [12], and the choice of the principle of automatic control (by deviation, by disturbance), on the other hand [13].

Conventional systems for monitoring [14] and controlling [15] production processes are not automatic control systems. These are information support systems for the operator to control tool conditions [16] and machining processes [17]. Therefore, unlike automatic control systems, they reach the commercial level in general for machining [18] and particularly with an active disturbance rejection control [19]. Some examples are spindle monitoring and power monitoring are presented in the research works [20] and [21], respectively.

# 3 Research Methodology

## 3.1 Machining Technology Influence on the MM Design

The following is a description and principle of operation of the latest ball-bearing screw converter design, which has shown reliable results as a comparator and force converter in mechatronic "action-counteraction" systems in machining. It includes a non-magnetic (textolite) body 1, in which a kinematic ball-bearing pair "screw-nut" (ball-bearing screw) with screw 2 (aka spindle) and nut 3 is installed (Fig. 1).

This pair is not self-braking, i.e., screw 2 can perform angular and reciprocating movements (concerning nut 3) in both clockwise directions, while the rotational movement of "screw" 2 is set by "nut" 3. A pair of "screw-nut" is fixed in housing 1 on two ball bearings 4 which allows both the "nut" 3 to rotate freely about its longitudinal axis and the "screw" 2 to carry out linear movements along the same axis.

The following are marked in Fig. 1: $Q$ is the weight (gravity) of MM moving parts, N; $F_{ed}$ is the electrodynamic force acting on the spindle, N; $F_{ed}$ is the electromagnetic force acting on the spindle, N. The rotational movement on the ball-bearing screw converter nut is transmitted through bypass coupling 5 from motor 6. The linear movement of spindle 2 is carried out due to the oppositely directed forces $F_{em}$ and $F_{ed}$, applied to its axis. This allows the spindle to smooth helical movements inside the "nut" without backlash and jamming.

Nut 3 is a source of rotational motion from the drive motor 6. It is made of non-magnetic material (brass, bronze, titanium alloy) and is a hollow cylindrical body (Fig. 1, a, b, c), on the side surface of which a two-start slotted groove is made with step $t$ at the angle of inclination $\alpha$. This groove performs the function of a two-start thread with

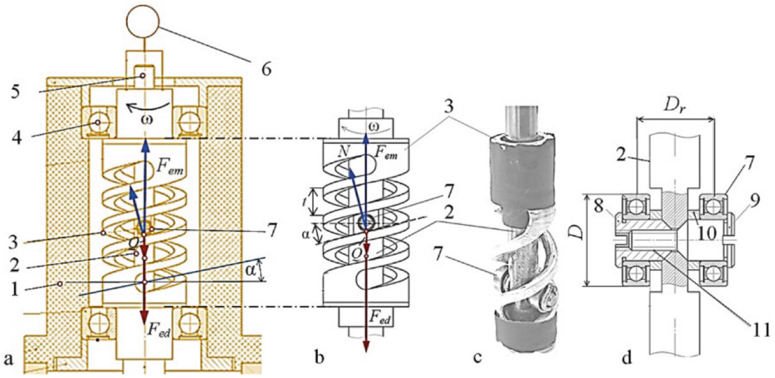


**Fig. 1.** Designing the ball-bearing screw converter.

the same pitch and angle. From the ends of the "nut" 3, it is equipped with two guide bushings (upper and lower) rigidly fixed inside it (not shown in Fig. 1). The bushings are made of non-magnetic material (fluoroplastic), which has a low coefficient of sliding friction. They provide the possibility of a smooth multidirectional helical movement of the spindle ("screw" 2) relative to the "nut" 3.

Screw 2, also known as the spindle, installed inside nut 3, is made of titanium alloy. This allows for reducing the MM moving part weight. On screw 2 (spindle), two support ball bearings 7 are fixed on the same axis. This axis is perpendicular to the longitudinal axis of the spindle. The outer rings of ball bearings 7 act as a bearing surface for the external thread of the "screw" 3 in a non-self-locking "screw-nut" connection. They provide the required mutual axial position of screw 2 relative to nut 3. Bearings 7 are fastened together by threaded tightening elements 8 and 9 (Fig. 1, d). To eliminate the error in the relative position of the bearings 7 and the spindle 2, spring washers (compensators) 10 are provided (Fig. 1, d), and the gaps in the threaded connection 11 are filled with sealant.

Such a design of the ball-bearing screw converter makes it possible to implement the control-configured MM with a dynamic balance of oppositely directed forces and torques that inevitably arise during machining.

When assembled (Fig. 1, c), the ball-bearing screw converter transforms the rotation of "nut" 3 and the reciprocating movement of "screw" 2 into the screw movement of the latter relative to nut 3. This is necessary to ensure a dynamic balance of forces and torques arising during system operation.

### 3.2 Control Configured Elements

The rotation of the spindle with the tool is provided by the drive of the main movement, and its reciprocating movements are provided by the joint action of three forces (Fig. 1): $Q$, $F_{ed}$, and $F_{em}$, N. Moreover, $Q = mg$, where $Q$ and $m$ are the weight (in N) and mass (in kg) of MM moving parts; $g$ is free-fall acceleration, м/s$^{-2}$.

The electrodynamic force $F_{ed}$ (in Newtons) acting on a current-carrying conductor of length $l$ (in meters) in a magnetic field with induction $B$ (in Tesla) can be found based on the well-known dependence for the Ampère force [1]: $F_{ed} = k_{ed}BIl$, where $k_{ed}$ is an experimentally determined coefficient.

The electromagnetic force $F_{em}$ (in Newtons) created by the coil with current (solenoid) can be found by the equation [1]

$$F_{em} = k_{em}B^2S, \tag{1}$$

where $k_{em}$ is the coefficient determined experimentally; $S$ is the effective cross-sectional area of the solenoid, $m^2$.

At the beginning stage of the cycle of the technological operation of processing, in which $F_{ed} = 0$, the forces $Q$ and $F_{em}$ during the execution of this cycle remain constant, and for this stage of the cycle, the condition is fulfilled: $F_{em} \geq Q$ which is close to the equality $F_{em} = Q$.

The force $F_{ed}$ is a variable value and can be programmatically changed in the range: $0 \leq F_{ed} \leq [P]$, where $[P]$ is the allowable axial load on the drill (in Newtons), while simultaneously applying a torque to it, N·m.

A wide range of force change $F_{ed}$ allows implementing three modes of MM operation: (1) accelerated approach of the tool to the machining zone; (2) working feed which provides the required value of power parameters (axial force and torque); (3) removal of the tool from the cutting zone (periodic during drilling and final at its completion).

Let us take a closer look at these three modes.

1. The approach of the tool to the cutting zone is provided by software with two counteracting forces $F_{ed}$ and $F_{em}$, on the spindle, the ratio between which allows selecting the necessary feeds of the tool with its accelerated approach and working stroke, which begins when the drill initially touches the surface to be machined.
2. The optimal power mode of the machining process (for example, cutting while drilling) is carried out by the forces $F_{ed}$ and $F_{em}$, while the value of $F_{ed}$ along the length of the processing is changed programmatically at $F_{em} =$ const, which ensures the optimization of cutting modes. The cutting resistance torque $T_{cut}$ that occurs in the machining zone is one of the power components involved in the dynamic balance of the spindle in its axial direction. This torque acts through the tool and the spindle on the ball-bearing screw converter, ensuring optimal machining process power parameters.
3. The removal of a tool (for example, a drill) from the cutting zone is realized by the joint action of two oppositely directed forces $F_{ed}$ and $F_{em}$. Periodic and final removal of the tool during drilling is performed to clean it from chips and after the end of processing, respectively. By changing the ratio between the forces $F_{ed}$ and $F_{em}$, it is possible to control the withdrawal tool speed from the hole. The maximum withdrawal tool speed is reached with $F_{ed} = 0$.

The described principle of operation of the ball-bearing screw converter corresponds to the control-configured MM for which maneuverability is a priority property. This is achieved by including in the balanced system of forces the mechanical resistance of the external environment as a necessary and active component of this system. In this system, oppositely directed forces are $F_{ed}$ and $F_{em}$ in "dynamic equilibrium", which is stabilized by the automatic control system "by disturbance".

Thus, a software change in the magnitude of one force $F_{ed}$ allows implementing many options for performing technological strokes and operations, including intermittent, vibrational, or pulsed machining. For example, when drilling, the axial force and torque take on the values and directions determined by this technological process requirements.

### 3.3 A Mechatronic Mechanism Mathematical Model

As a power and kinematic mechanism, the ball-bearing screw converter participates in dosing the forces and torques applied through the spindle to the tool, and each "dose" must be sufficient for the high-quality implementation of the process at any moment of its course. It is known, for example, that when drilling through deep holes, the axial force and cutting torque should not be constant over the entire drilling depth. So, for example, at a depth of 0.05*L* (drill plunge), the forces should essentially differ in magnitude from those power parameters of the cutting mode that are realized at a depth of 0.5*L*, and completely different cutting forces are assumed at the drill exit from the hole being drilled, i.e., at a drilling depth of 0.95*L*, where *L* is the drilling depth.

Thus, the body for dosing forces and torques in the system of adaptive control of cutting processes must be programmable and flexible. In addition, any automatic control (regulation) system assumes the presence in it of a body for comparing the value of the actual state of the controlled parameter with a given (preset) value. Such a role in the considered MM is played by the ball-bearing screw converter, which provides not only a comparison of the force load in the cutting zone with a programmed value but also acts as a dispenser of normalized forces supplied to the cutting zone.

Let us call a "dose" a part of the sum of forces $Q$,$F_{ed}$, $F_{em}$, and trace how the "dose" which is necessary for the implementation of the programmed forces in the cutting zone is "separated" from the "whole". This can be traced by analyzing successively the schemes of action of the forces presented in Fig. 1, a, b, d, and Fig. 2.

Let us replace the set of forces $\overline{Q}$, $\overline{F}_{ed}$, and $\overline{F}_{em}$ (Fig. 2) with one resultant force $2\overline{T}$, i.e.

$$2\overline{T} = \overline{Q} + \overline{F}_{ed} + \overline{F}_{em}. \tag{2}$$

Let us transfer the resultant force $2\overline{T}$ to the point $C$, formed by the intersection of the axes $S - S\ and\ C - C$ (Fig. 2).

Forces $\overline{Q}$ and $\overline{F}_{ed}$ are directed to the surface to be machined, and the force $F_{em}$ is directed "from" the same surface.

Since the vectors $\overline{Q}$, $\overline{F}_{ed}$, and $\overline{F}_{em}$ are located on the same straight line, the modulus of the resultant force can be found in the equation

$$2T = F_{ed} + Q - F_{em}. \tag{3}$$

Since the force $2T$ is distributed through two ball bearings, it is possible to operate with the force $T$, with the transfer of its action to the points lying on the axis of these ball bearings.

The force vector $T$ must be transferred to the point $O$ (taking into account the parallel transfer rule), in which the outer ring of the support ball bearing is forced to close with the inclined plane of the "nut" turn.

As a result of such a transfer, the reaction $\overline{N}$ occurs (Fig. 2) at the point $O$, and $N = T\cos\alpha$. Further, it is necessary to decompose the reaction $N$ into two components ($N_x$, horizontal) and $N_z$, vertical), as well as determine their values as follows (Fig. 2, b): $N_x = N\sin\alpha$ and $N_z = N\cos\alpha$.

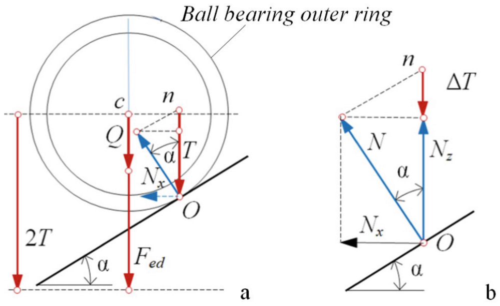


**Fig. 2.** Force interacting of a screw-spindle ball bearing with the nut threaded surface (a) and the same on a scale of 2:1 (b).

That is why

$$N_z = T\cos\alpha\cos\alpha = T\cos^2\alpha. \tag{4}$$

In turn

$$\Delta T = T - N_z. \tag{5}$$

That is

$$\Delta T = T - T\cos^2\alpha = T\left(1 - \cos^2\alpha\right) = T\sin^2\alpha. \tag{6}$$

Thus

$$\Delta T = 0.5(Q + F_{ed} - F_{em})\sin^2\alpha \tag{7}$$

Focusing the two components of $\Delta T$ on one central axis, we get

$$2\Delta T = \left(mg + k_{ed}BIl - k_{em}B^2S\right)\sin^2\alpha. \tag{8}$$

Equation (8) can be used to perform practical calculations for the created MM, configured by control, including the linear impulse definition for the resultant force $2\Delta T$.

# 4 Results and Discussion

## 4.1 Influence of the Helical Groove Angle on the Axial Machining Force

Representing Eq. (8) in dimensionless form, we get

$$\eta = \frac{2\Delta T}{\left(mg + k_{ed}BIl - k_{em}B^2S\right)} = \sin^2\alpha. \tag{9}$$

Now it is possible to build a graph (Fig. 3), which allows getting visual recommendations on the value of the helical groove inclination angle α for the implementation of various technological processing modes: zone *A* – nanotechnology; zone *B* – microtechnology; zone *C* – macrotechnology.

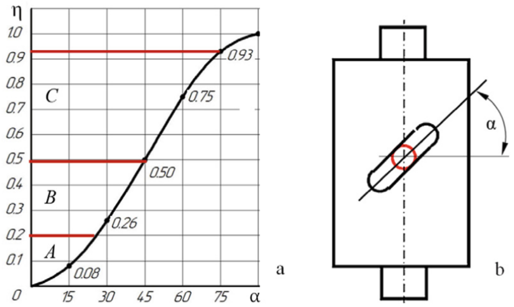


**Fig. 3.** Influence of the helical groove angle α on the dimensionless axial force η (a) and the location of the angular dimension α (b).

## 4.2 Results of Experimental MM Studies

Experimental studies to establish the MM technological capabilities and areas of its effective application were carried out in Germany (Stuttgart Technical University in cooperation with HUGO RECKERTH GMBH) and Ukraine (National University Odessa Polytechnic and Odessa State Academy of Civil Engineering and Architecture). Research has been carried out in many areas, including: 1) achieving dimensional accuracy and quality characteristics of the surface layer of parts made of difficult-to-machine materials (research in Germany); 2) establishing a nomenclature of materials to be machined with unusual physical and mechanical properties, as well as improving the MM design in the direction of improving its quality indicators (research in Ukraine).

Another direction of successful experimental work is engraving inscriptions on granite slabs with a diamond tool with a working part diameter of 0.7 mm (rotation speed of 20,000 rpm, and water as coolant). Results: the absence of macro- and micro-chipping of solid mineral inclusions in the material to be processed.

Studies of the developed MM in machining superhard and anisotropic materials showed the expediency of endowing the MM with sensory organs, which made it possible to identify the opportunity for new product innovation. The MM peculiarity, established in previous studies, associated with tactile sensitivity of the working body of a technological machine (analogous to a living organism's properties), is a prerequisite for creating intelligent technological machines of various natures and purposes. This opens the way for the production of mechatronic technological systems of a new generation that cover the entire technosphere of human activity, for example, medical, military, and industrial equipment.

## 5 Conclusions

The following features of modern difficult-to-machine constructional materials, including ceramic and composite ones, have been established: increased hardness, pronounced anisotropy of properties, and susceptibility to defects. These features make it challenging to apply existing machining technologies and lead to the need to develop fundamentally new technologies for their high performance and defect-free machining on CNC mechatronic machines.

A new paradigm of the control-configured mechatronic mechanism has been formulated based on a technology-oriented approach, according to which the functioning of this mechanism is determined by features of high performance and defect-free machining, for example, on CNC machines. Such a technology can be realized due to the combined action of a programmable electrodynamic force and the counteraction of the environment. These two forces (action and counteraction) "configure" the mechatronic mechanism, i.e., give it the ability to function according to the machining technology needed. These are the main advantages of this mechatronic mechanism and the results' practical significance.

The design of the mechatronic mechanism and its mathematical model have been developed, which show the possibility of regulating the power machining parameters (cutting force and torque) in a wide range, i.e., from nano- and micro- to macro-values. Recommendations are given on the value of the helical groove angle of the ball-bearing screw converter for implementing various technological operations connected with the machining of the above materials.

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