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Smart drilling that meets technological requirements

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ABSTRACT

In manufacturing technology, hierarchical control remains one of the most relevant topics. When applying multiple control levels, the most complex challenge is achieving interaction between the different hierarchical levels within a unified mechatronic technological system (MTS). The successful integration of equipment results in an intelligent control system. This article discusses the results of experiments to determine the axial cutting force as a function of various combinations of electric currents in the stator and armature windings of a linear mechatronic actuator. The MTS consists of a two-level control system: a CNC machine tool and a mechatronic spindle.

At the upper control level, the CNC device provides the necessary axial feed of the entire mechatronic spindle, based on the requirement to maintain the operational range for automatic regulation of cutting force parameters at the lower control level. The lower control level is represented by an intelligent mechatronic mechanism designed to stabilize or programmatically change the axial force and cutting torque. This means the force parameters are adjusted according to the technological requirements for processing parts made from anisotropic materials (e.g., polymer composite materials in engineering, living bone tissue in orthopedic surgery, etc.). Consequently, the anisotropy of material properties necessitates changes in drilling kinematic parameters to ensure the programmed provision of the specified cutting force parameters.

Control at the lower level is implemented via two coils of the linear actuator. These coils interact with each other (through the interaction of their magnetic fields) and alter the axial feed force of the drill. The experimental results allow for determining the operational range of force parameters for the dynamic motion of the tool according to technological requirements, ensuring the necessary processing quality while maximizing cutting tool life.

Keywords: Smart drilling; adaptive control; axial drilling force; cutting torque; two-level control system; anisotropic materials

Relevance. The precision of machine tool operations is a key indicator of equipment efficiency and unequivocally influences the quality of the outcome. During material processing, the equipment encounters variations in the material's structure, quality, and layer characteristics. This affects the processing time as well as the equipment's durability due to fluctuations in the applied force and processing temperatures.

The integration of monitoring instruments for real-time response to changes related to the specific properties of the workpiece material enhances equipment durability and operational quality. Based on experience in implementing technologies within specific industrial manufacturing sectors, it has been noted that the adoption of mechatronic technological systems accelerates the equipment's reaction to necessary process adjustments compared to corresponding mechanical control means.

Currently, all setup and operational procedures for CNC machine tools are conducted using standard drilling parameters for various material types. These standards were established during equipment testing and ratified as baseline conditions for drilling. However, such settings fail to account for specific material structural features, quality variations, the presence of defects in parts, and numerous other factors. Consequently, a primary drawback during the operation of CNC

machine tools is the absence of in-process software adjustment during machining, for instance, when drilling anisotropic materials in accordance with the technological requirements for productivity and quality.

Implementing a smart drilling mechanism in CNC equipment necessitates the creation of a two-level control system, which makes a substantial contribution to solving the problem of flexible response to process variations when machining anisotropic materials.

Literature Review. Currently, the theory of hierarchical control remains far from ideal, and no established rules exist. The criteria for interaction between different levels to achieve an acceptable control outcome are still unknown. A significant achievement in this field is the known "rule of authority levels," where managerial intelligence is hierarchically distributed according to the principle of increasing precision with decreasing intelligence. This phenomenon is often observed in hierarchical systems [1].

The situation in the field of drilling and bone cutting in medicine could be radically transformed by applying technologies used for machining metals and composites, alongside feedback and adaptive control, which are frequently utilized within the well-known "Industry 4.0" framework [2].

The response of a mechatronic feedback system to an unexpected deviation is delayed, and such a closed-loop system is not prepared for random, i.e., unforeseen, deviations [3]. A drawback of a mechatronic system operating on the "disturbance compensation" principle for controlling force parameters in the processing zone is that during the execution of a dimensional machining program, areas with altered physico-mechanical properties of the part material result in dimensional errors manifesting as unprocessed material sections [4].

The well-known control principles – "error-controlled" and "disturbance compensation" – in modern control theory are supplemented by a new direction: distributed and hierarchical control systems with four levels (bottom-up): component level, data pre-processing level, intelligent pre-processing level, and top level [5].

The idea of hierarchical (e.g., two-level) control of the cutting tool's axial movement is based on a systems approach that ensures the necessary interaction between the upper and lower control levels [6]. It is worth noting additional literature that was utilized. This includes methodologies of scientific research [7], composites and drilling [8], and works on the physics of electromagnetism [9].

Research Objective. The aim of this work is to create mechatronic technological systems for processing anisotropic materials, featuring fast-response adaptive control based on the utilization of a force electromagnetic field. This field can simultaneously increase and decrease the force applied during material processing, thereby implementing intelligent control on the machine tool.

Methodology. The proposed design of a two-level control system creates equipment for sensitive control of the mechanical processing of parts made from anisotropic materials. The scientific research consists of two parts: theoretical and experimental. Decision-making was structured around stages of quantitative and qualitative analysis, followed by synthesis based on the obtained results.

At the first stage, an analysis of the research object and subject was conducted. The object is a technological operation, an example of which is drilling small-diameter holes (up to 3 mm) in parts made from anisotropic materials. The subject is a two-level automatic control system of a hierarchical type, dealing with the force and kinematic parameters of mechanical processing.

At the second stage, corresponding technical systems, designs, and processes (for processing and control) are developed to achieve the research objective. The design systems include a block with stator and armature coils, which ensures the stabilization of mechanical processing force parameters or modifies the force according to a specified machining technology. For instance, resistance should be minimal when the drill enters the workpiece or when it needs to exit the

material. Processing within the body of the part corresponds to optimal values of axial drilling force and cutting torque.

The research was based on the following methodological approaches:

1. Modeling of the Armature and Stator Coil Block. An equipment model was created, enabling the investigation of changes in force and temperature factors during the processing of different material types using small-hole drilling in the 1-3 mm range.

2. Optimization of the Control Block's Influence on the Drilling Process and Selection of the Operational Range for the Coil Gap. This ensures an optimal distance between the coils without losing the power of the electromagnetic fields.

3. Control of the Smart Drilling Process. Implementation of a system for directly influencing changes in the drilling process force indicators through the interaction of the stator and armature coils. This control must be adaptive and intelligent to adjust the drilling process depending on variations in the anisotropic materials.

To modernize and enhance the CNC technical equipment for achieving adaptive control during material drilling, a block with two coils acting as the stator and armature embedded in the spindle was utilized. A gap is maintained between them for dynamic motion, allowing control of the axial drilling force while keeping the CNC machine tool feed constant. Voltage is supplied to each coil separately from different power supply units to ensure the required resistance between them. Furthermore, load cells are installed to record the force acting on the material (Fig. 1).



Fig. 1. General view of the machine tool with a two-level control system

To record the parameters for the analysis of the conducted experiments, let us designate them as follows: U_{st} – voltage on the stator coil winding; U_{cr} – voltage on the armature coil winding; L – gap between the coil end faces; F – axial force (Fig. 2); I_{st} – current in the stator coil winding; I_{cr} – current in the armature coil winding (Fig. 3).

Research Results. The study was conducted using two integrated systems: a CNC machine tool responsible for the axial feed of the mechatronic spindle (the machine's vertical moving platform housing the spindle with two coils exhibiting mutual resistance with a gap for drill feed adjustment), and the mechatronic spindle assembly itself.

1. During a stable drilling process, i.e., when the force parameters remain within the programmatically permissible values (standard material drilling parameters), the spindle functions as an integral component of the CNC machine tool. Control is executed within the XYZ working coordinates by the CNC system. Drilling accuracy in this regime is determined solely by the technical properties and characteristics of the machine tool.

2. During the drilling operation, the CNC system does not account for the specific characteristics of anisotropic materials. Therefore, integrating the electrical coil control system into the spindle introduces the capability for intelligent control in response to variations in the vertical feed force. If the force applied to the material is insufficient, the armature coil increases the load on the drill to compensate for the force deficit. Conversely, when the force is excessive, the stator coil displaces the armature coil to reduce the pressure.

To configure the interaction between the two systems, an analysis of the operating point is necessary. This point is defined as the state where the stator and armature coils exert equal repulsive force on each other, stabilizing them in a stationary relative position. This establishes the baseline spindle movement interval for responding to variations encountered in anisotropic materials.

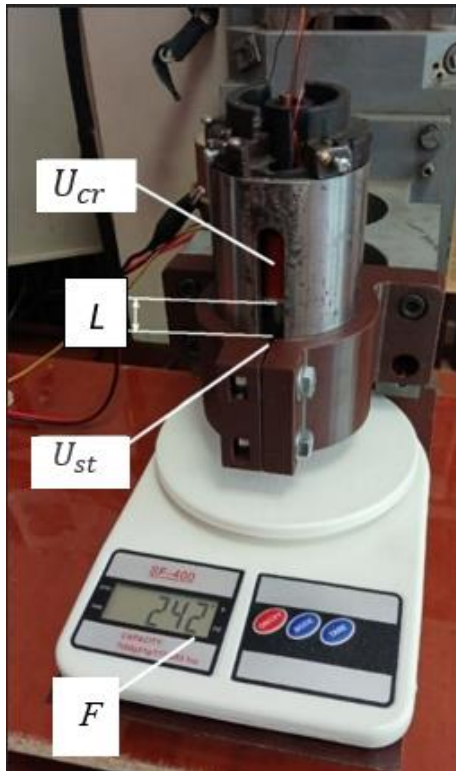


Fig. 2. Spindle with two embedded coils and a gap L between them

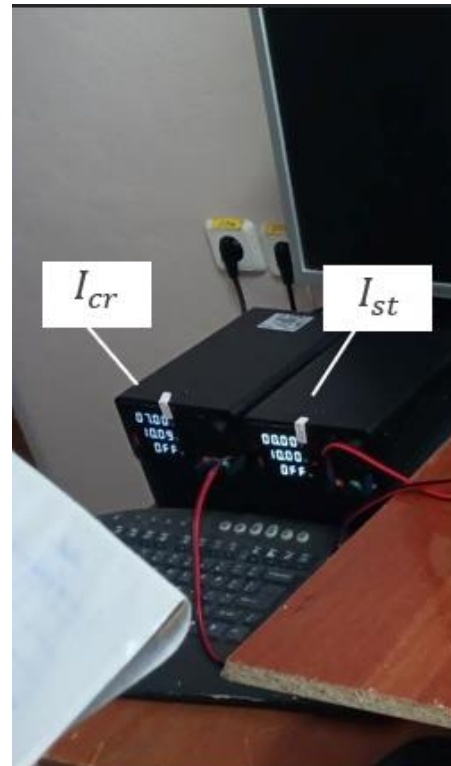


Fig. 3. Power supply units for independent current supply to the stator and armature coils

The experiments were conducted with different configurations of stator and armature coils, varying the inter-coil gaps and polarity. Drilling was performed on materials of identical density, while the feed rate on the CNC machine tool remained constant for all test cycles. Drills with a diameter of 1.2 mm were used. The operational gap ranges between the coils were set as follows: (1) 2-3 mm, (2) 5 mm, (3) 7-8 mm. The voltage applied to the stator coil winding was fixed within a single experiment at values of 0 V, 2 V, 4 V, and 6 V. The voltage supplied to the armature coil was varied within a range from 0 V to 16 V (Fig. 4). The current in the armature coil winding and the axial force acting on the material during the constant feed from the CNC machine tool were recorded.

As a result, graphs (presented below) were compiled, illustrating the dynamics of the axial force change under the influence of the dynamically varying armature coil current, while other parameters on the machine tool remained static. Let us consider the results concerning the influence of changes in the armature coil current supply, under the condition of zero current supplied to the stator coil, and the overall research findings across different operational ranges.

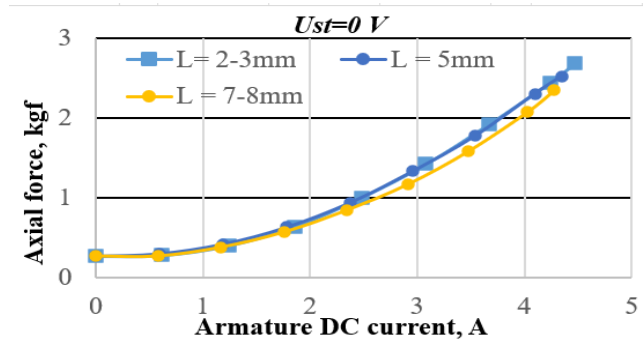


Fig. 4. Change in Axial Force with Increasing Armature Coil Voltage under De-energized Stator Coil Condition

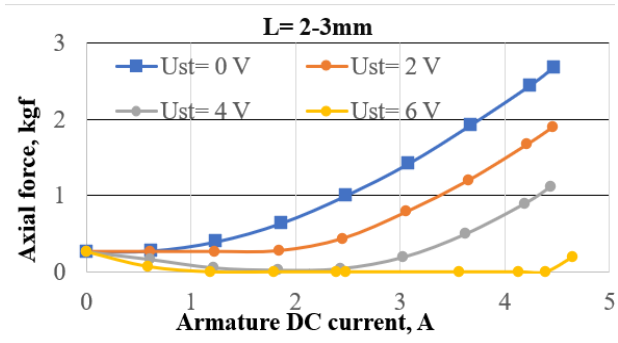


Fig. 5. Indicators of axial force variation under fixed stator coil supply parameters and variable armature coil input at $L = 2-3$ mm

The provided graph (Fig. 4) demonstrates that an increase in the armature coil current amplifies the drill's impact force on the material under a constant feed rate from the CNC machine tool. To achieve optimal performance, it was necessary to experimentally determine the operating point corresponding to the static indicator of the material impact force. This enables the stabilization of the drilling process for a consistent axial force magnitude; any deviation from this value activates the intelligent control system to stabilize the machine tool's operation. To analyze the operational voltage range for the stator, a graph compiling data from various experiments was constructed.

The first graph depicts the experimental results obtained using the smallest operational range. The distance between the stator coils and the armature coil was only 3 mm. Zero drill thrust force on the material is achieved when a voltage of 4 V is supplied to the stator coil, corresponding to a current supply of 1.24 A, while the voltage on the armature coil varies in the range of 4 to 8 V, equivalent to a current range of 1.22 to 2.43 A (Fig. 5). When utilizing this operational range, a balance of opposition between the two coils is established.

The subsequent graph presents the experimental results obtained with an operational range of 5 mm. The zero thrust force is likewise achieved at a stator power of 4 V, corresponding to a current supply of 1.13 A, while the armature coil voltage was varied within the range of 4 to 8 V, equivalent to a current range of 1.17 to 2.35 A (Fig. 6). This operational range similarly ensures the attainment of the required result, as did the previous one. However, the greater distance between the coils allows for a wider range of variation.

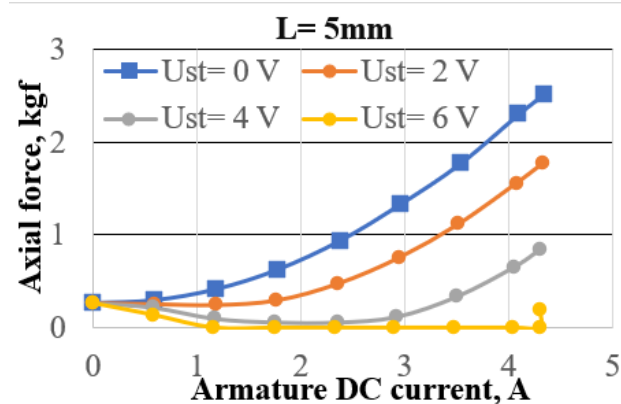


Fig. 6. Indicators of axial force variation under fixed stator coil supply parameters and variable armature coil input at $L = 5$ mm

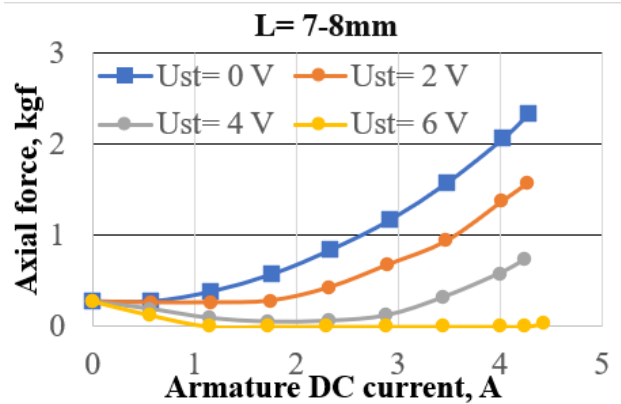


Fig. 7. Indicators of axial force variation under fixed stator coil supply parameters and variable armature coil input at $L = 7-8$ mm

The graph (Fig. 7) clearly indicates that with a gap of 7-8 mm and a stator coil voltage of 4 V (corresponding to a current of 1.12 A), the pressure force on the material reaches nearly zero when the armature coil voltage varies in the range of 4 to 8 V (corresponding to a current range of 1.15 to 2.32 A). This operating point corresponds to the balance of opposition between the two coils and eliminates the error caused by the vertical forces from the CNC machine feed.

Based on experimental research, a coil gap range of 7 to 8 mm was established as the operational range. This gap provides a sufficient interval for responding to structural variations in anisotropic materials without compromising the force interaction between the coils via their electromagnetic fields.

This operational range was determined by averaging all analyzed parameters. It provides a sufficient gap between the coils, allowing for responsive adjustments to variations in the drilling process. Furthermore, the electromagnetic opposition utilizes the minimum possible power, leading to cost savings in production.

During repeated experiments under identical conditions, the error between results averaged between 3 % and 4 %. These indicators should be reduced by employing analog controller instruments for data acquisition, which would enable recording values within the drilling operational range and capturing a more precise average value for a single experiment.

Conclusions. 1. The implementation of a two-level control system on CNC machine tools will enhance the quality of processing parts made from anisotropic materials by introducing adaptive control for maintaining stable drill feed under varying conditions.

2. This technology will improve control over complex operations that typically require either high-precision and expensive equipment or a highly skilled operator relying on extensive experience. For instance, in surgical procedures involving bone drilling, where precision and quality are paramount; such a two-level control system will mitigate the influence of the human factor on work quality and eliminate so-called iatrogenic processing defects.

3. In the future, to improve the equipment and automate drilling control, it is necessary to incorporate controllers. Currently, the operational parameters of the machine tool are fixed, and materials are processed according to the axial force specified in the control program. The machining of anisotropic materials, however, requires real-time adjustments during the drilling process. This variation is manifested in the gap between the coils and, in perspective, should be monitored by a sensor that detects the displacement of the central point within the gap.

If the mean point shifts toward the stator, an increased voltage should be applied to it in order to raise the resistance and return the mean point to its nominal position within the inter-coil gap. The same control principle should be applied to the armature coil. Such monitoring will enable the adjustment of the axial load force instantaneously, during the process itself, rather than after the completion of the predefined machining program.

4. The utilization of electromagnetic fields in mechatronic technological systems significantly enhances the instantaneous response to changes in the drilling process. By increasing or decreasing the current in the stator or armature coils, it becomes possible to adaptively correct the force load on the cutting tool, ensuring high productivity and processing quality. Simultaneously, if the changes in the coil gap reach the minimum or maximum permissible values, the intelligent system must notify the CNC machine tool of the need to change the programmed feed rate. This requires integrating a coil position change controller and a corresponding automatic control system.

5. To obtain accurate experimental results, a computerized system for collecting and analyzing experimental data should be employed. This system must display data arrays at required time intervals, for instance, with a frequency of up to 200 Hz. This will ensure the accuracy of the experiments and prevent errors during calculations and result recording.

6. A distance of 7 mm was selected for the operational range, as it provides a sufficient interval

for conducting further experiments. However, the provided graphs for gaps of 2 mm and 5 mm demonstrated a similar relationship with variations in the current supply between the coils. This indicates that these ranges can likewise be used for specific applications that require the operation of tools with small dimensions.

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Розумне свердління, яке забезпечує технологічні вимоги

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АНОТАЦІЯ

У технології машинобудування однієї із найактуальніших тем досі вважають ієрархічне керування. В застосуванні декількох рівнів управління найскладнішим процесом являється досягнення взаємодії на різних рівнях ієрархії у рамках єдиної мехатронної технологічної системи (МТС). При вдалому поєднанні обладнання отримає інтелектуальну систему керування. У статті розглянуто результати проведених експериментів щодо визначення осьової сили різання у залежності від поєднань різних за величиною електричних струмів обмоток статора та якоря в лінійному мехатронному актуаторі. МТС складається з дворівневої системи керування: металорізального верстата з ЧПК та мехатронного шпинделя.

На верхньому рівні керування пристроєм ЧПК забезпечується необхідна осьова подача всього мехатронного шпинделя виходячи із умови забезпечення робочого діапазону автоматичного регулювання силових параметрів різання на нижньому рівні керування. Нижній рівень керування представлений інтелектуальним мехатронним механізмом, який призначений для стабілізації або програмної зміни осьовій силі та крутного моменту різання, тобто силові параметри змінюються відповідно вимогам технології обробки деталей, які вироблені з анізотропних матеріалів (полімерні композиційні матеріали в техніці, жива кісткова тканина в ортопедичній хірургії тощо). Таким чином, анізотропія властивостей матеріалів вимагає зміну кінематичних параметрів свердління виходячи з необхідності програмного забезпечення вказаних силових параметрів різання.

Керування на нижньому рівні відбувається завдяки двом котушкам лінійного актуатора. Ці котушки впливають одна на одну (через взаємодію магнітних полів кожної котушки) та змінюють осьову силу подачі свердла. Результати проведеного експерименту дозволяють визначити робочий діапазон силових параметрів для динамічного руху інструмента відповідно технологічних вимог, щоб забезпечити необхідну якість обробки при максимальній стійкості ріжучого інструмента.

Ключові слова: розумне свердління; адаптивне керування; осьова сила свердління; крутний момент різання; дворівнева система керування; анізотропні матеріали