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Adaptive control of mechatronic machine-tool equipment

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Abstract

In this paper the method for designing a functional structure of mechatronic modules based on the developed classification of functional subsystems and the proposed turning machine modular structure is presented.

Keywords: functional subsystems, modular structure, adaptive computer control.

1. Introduction

Mechatronic machine-tools are well known for their improved accuracy of manufacturing while being controlled by computers. However, the issues of improving the equipment technology capabilities with regards to the of quality of manufactured, processing efficiency, and cost reduction during production still remain valid.

At present, mechatronic machine tools are of two types: numerically controlled machines (NC machines) and machines with adaptive computer control (NC and ACC machines). NC machines are running a fixed pre-installed program, which remains the same during the whole manufacturing process. The exception is made only to correct the controlling device position. At the same time, NC and ACC machines of the second type support program modification while running by connecting AC loops, which take into account possible changes in the process conditions. Such conditions include modification of machine-finish allowances, tool wear, thermal and energy strain of machine frame, features of cutting process, etc. Equipment performance can be considerably increased if actual conditions are taken into account during processing. With this in view, it can be stated that mechatronic machine tools of the second type feature enhanced technological capabilities. Therefore it will be advantageous to make a provision for a complex adaptive computer control when designing and operating mechatronic machine tools of this type.

2. Design of a mechatronic machine tool

As a mechatronic machine tool (MMT) is a main manufacturing system consists of mechatronic modules or devices performing various functions in the course of a controlled part production [1].

Features of functional subsystems and their configuration are decided depending on the required functions to automate manufacturing of parts [2]. Configurations of functional subsystems of various levels supported by mechatronic machine tools are summarized in Table.1. Based on the system approach, each subsystem (of a higher level) is viewed as a system for its constituent subsystems of a lower level.

Table.1. Configuration of functional subsystems of mechatronic machine tools.

Functional subsystems	1^{st} level, Responsible for various types of operating movements	Mechatronic modules: basic, simple and combined, specialized
	2^{nd} level, Responsible for parameters of operating movements	Subsystems of mechatronic modules to control movement start/stop, reversing, rate, motion, and trajectory
	3^{rd} level, Supporting features of implementation of operating movement parameters	Subsystems supporting features of movement start/stop, reversing, rate, motion and trajectory
	4^{th} level, Responsible for various types of actions when controlling operating movements	Subsystems supporting types of control actions when implementing the features of operating movement parameters - NC, -NC and ACC

The configuration of subsystems is determined by the purpose of equipment and the requirements of the manufactured parts and the specific production environment. Subsystems of the first level can be classified as modules supporting operating movements and their parts. It is expected that a mechatronic machine module either on independently or in combination with other modules must provide for the solution to a complex control problem [1], including a manufacturing process, forming of parts, control of automatic equipment, and performance of auxiliary functions.

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Depending on their use, machine tools can be subdivided into basic, auxiliary and specialized ones. Basic modules can be of a forming type, i.e. they produce parts of the required quality using a set of subsystems. They are classified into those of principal movement and supply modules, which can be either simple or combined. A combined module is a structural combination of two or more simple modules with a possibility to match corresponding control subsystems and perform complex movements. Specialized modules produce forming if used to achieve the required part parameters when structural features and operation conditions are considered. Their basic functions are to correct rotational or reciprocating micro-motions. Auxiliary modules are designed to perform movements which support part processing operations.

The analysis of the available functions necessary to achieve the required specifications of space and time of the operating movements [1] revealed that functional subsystems of the 2^{nd} level include those controlling start and stop (conventionally designated as S&S), reversing (*MR*), rate (*MRt*), motion (*Mt*), and trajectory (*MT*). Subsystems supporting movement trajectories fall in the category of combined modules (or of a combination of simple modules) performing complex operating movements.

Subsystems of the 2^{nd} level are subdivided into subsystems of the 3^{rd} level depending on specific requirements. Functional subsystems of the 2^{nd}, 3^{rd}, and the 4^{th} levels are conventionally described with the first letters of their names. For example, *MA*, *MS* stand for subsystems providing movement acceleration and infinitely variable at movement start and slowdown. These subsystems control smoothness of movement and machine tool performance.

Data from cutting and equipment performance optimization are used as input to determine the 3^{rd} level subsystems. For example, the task of supporting processing conditions which produce the smallest equipment dimension wear with improved efficiency is growing in importance. This can be achieved by cutting temperature control and processing mode management in agreement with the dependencies specified [3]. The identification of vibration-free and precise operating modes of equipment is of vital importance [4].

The 4^{th} level subsystems differentiate by the specific types and features of control activities which are applied when running these subsystems. A peculiarity of popular NC machine tools is the application of direct or indirect program control of movement parameters [1]. Adaptive computer control of these functional subsystems can be used to achieve the operating movement or processing parameters. The best quality of manufactured parts can be provided by controlling modules of the processing parameters. To do this, in process measuring sensors should be included into a control loop.

The analysis of a specific machine tool modular structure enables to determine its technological capabilities. In order to determine design specifications and implement an efficient control solution, a modular structure should be used when designing a new machine tool.

3. Methods to increase the efficiency of mechatronic machine tools

In researches on the cutting process optimization, a statistical laws which should be taken into account when developing modular structures were determined [3].

To evaluate the wear resistance of cutting instruments and workability of steels and alloys, the relative linear wear or wear rate is a universal characteristic of dimensional life (independent of tool dulling) [5, 6]. Fig. 1 demonstrates the findings of such a study into the cutting speed effect on a cutting instrument wear rate for various combinations of tool and processed materials. For the combinations under consideration, these dependencies have a non-monotonic character with one or two minima corresponding to the optimal cutting speed.

The optimal cutting speed depends on the physical and mechanical properties of the processed and tool materials, shearing section and other cutting conditions. The optimal cutting speed for the material under study of the instrument cutting unit with various combinations of cutting speed, tool advance and geometry correlates with a constant temperature in a cutting zone as the optimal case [3].

Thus, research of temperature parameters in a cutting zone enables to both reveal the rather complex nature of corresponding physical phenomena and determine the optimal cutting mode parameters resulting in the most efficient process characteristics of edge cutting machining. The identified parameters can also be used for the system controlling machining speed (Fig. 2).

Temperature sensors (TS) measure cutting zone temperature. Its signal coming through a dead zone block (U_{cp}) is compared to the U_3 signal of a set-up unit SV using a comparing element. The voltage Uy from amplifier A comes to an operational unit regulator (OU) to support the predetermined value of a spindle speed.

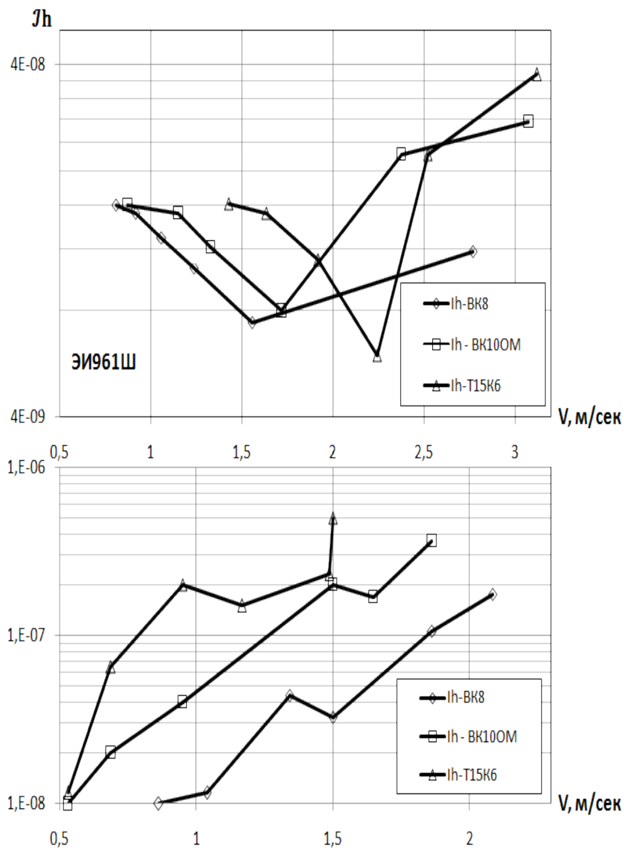

Fig. 1. Cutting speed effect on wear rate when turning Ni-based heat-resistant steel and Ti alloy by cutters made of various tool materials.

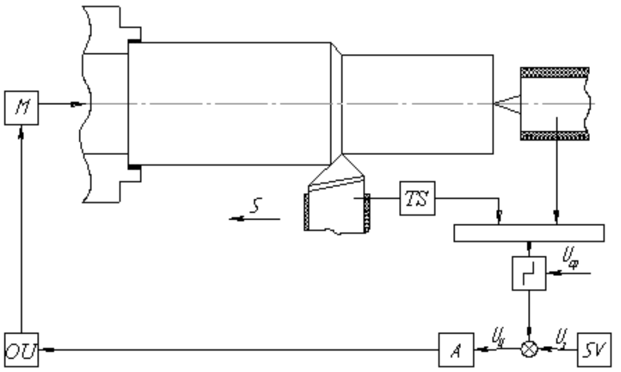

Fig. 2. Flow chart of a subsystem controlling the speed depending on the cutting temperature.

This flowchart uses a dynamic thermocouple in a cutting bit or a part as a feedback sensor. A cutter, a tail center, and a piece part are isolated from metal work elements of a machine tool to weaken the influence of foreign thermo-emf, produced which will impair the accuracy of temperature measurements.

The best performance with minimum instrument wear can be achieved by applying a speed control subsystem (Fig. 2) to change cutting speed or feed rate during processing at the known optimal and current cutting temperatures. With this in view, cutting sequence control algorithms can be determined to achieve improved parameters of part processing.

The research has shown that control of acceleration and slowdown of operating movements due to inertial forces allows the reduction of transient time, and enhances processing performance and accuracy.

Variable conditions and control parameters of machine tools are restricted by the equipment capabilities on processing accuracy, allowable load and the predetermined conditions of a typical process progress. Constraint systems used to control roughing and semifinishing processes are restricted with regards to power parameters, while systems controlling the finishing and semifinishing processing are restricted in feeding parameters. So, it is possible to develop algorithms controlling processing sequences to achieve the enhanced processing accuracy.

4. Method for designing a modular structure

Initial data include the type of machine tool studied (developed) and its primary purpose, information on processing sequence, and production requirements.

A modular structure is designed in the following order: analysis of processing patterns, determination of processing sequence algorithms, determination of module functional subsystems, development of a module flow-chart, design of a module structure.

When analyzing processing patterns, it is necessary to identify the methods of part forming, sequence of operating movements, and the features of processing sequences for a given machine tool with respect to the required performance indicators. Modular structure and the necessary functional modular subsystems are selected on the basis of design, kinematics, machine control system and classification analysis.

A module flowchart should presents a general view of module component parts, sensors, control links and data connections. The features of module component parts and sensor types are taken into account when designing a modular structure.

5. Example of a modular structure development

Following is the details of the developed module of a principal movement for NC turning machine to manufacture a part family of a bracket type made of Ti. The basic manufacturing characteristics of a principal movement module were determined on the basis of the analysis of technological conditions for a machine utilization: $n_{min} = 90$ min^{-1}; $n_{max} = 9600$ min^{-1}; $P_{el} = 9$ kW. The lathe 160HT was taken as for comparison.

On the basis of research results, module control algorithms were specified in detail to perform the required processing sequence on the machine tool:

- modification of acceleration and slowdown parameters in the course of rotation movement start or slowdown allowing for spindle unit vibration to reduce transient time and enhance performance;
- modification of spindle rotation rate and its maintenance at a high level applying the optimal cutting temperature parameter to enhance performance.

Using the classification of functional subsystems of machine modules, we managed to categorize functional subsystems of the module developed supporting the implementation of the processing sequence control algorithms.

The developed module differs from the corresponding module of a counterpart machine tool in the following subsystems:

- UB21, TB21 with acceleration and vibration sensors required;
- IS23 used to modify cutting speed with cutting speed and temperature sensors required.

The structure of the principal movement module when a drive spindle is used is shown in Fig. 3.

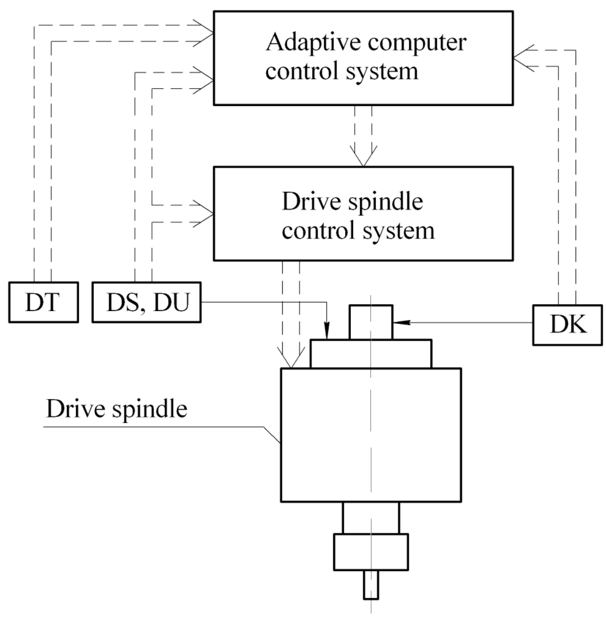

Fig. 3. Principal movement module structure.

A module of a drive spindle type has the following advantages: absence of auxiliary torque transmission units; a more compact layout and smaller drive dimensions; enhanced capabilities to support high spindle rotation rate, which enables the expansion of the family of processed parts and apply high-speed processing.

Weaknesses of the drive spindle arrangement include low power and performance when processing parts at a spindle rotation rate below the nominal one, and comparatively high cost. In this case, enhanced performance and processing accuracy can be achieved through a reduced time of start-up, slowdown and optimal cutting speed due to the better fit to the processing conditions.

6. Conclusions

1. It is advisable to apply the developed method for designing module functional structures based on the proposed classification of functional subsystems to implement a complex adaptive computer control of mechatronic machine-tool equipment.
2. It is advantageous to apply a principal movement module in the form of a drive spindle with customization to processing conditions when implementing high-speed processing. This module supports the modes of accelerated start-up, slowdown and optimal cutting speed according to operating temperature conditions.

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