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HYBRID MODELLING OF MACHINE TOOL WITH INTEGRATED COOLING SYSTEM

In this paper, a method of hybrid modelling of machine's mechanic structure together with mechatronic cooling system of its body is presented. In this method, a FEM model, traditionally used for thermal analyses of machine's thermal behaviour, has been integrated with mechatronic model of cooling system, implemented in MATLAB. In such way, a hybrid model has been created, allowing to simulate the control of machine body cooling process. Applied simulation of cooling the region of body, adjacent to the guide, illustrates the possibility of controlling the temperature in chosen points of the machine tool, in transient state, which would ensure minimal body deformations, small enough not to require compensation, which is generally hard and of limited precision. Thermal model of machine tool has been built with the use of SATO system [1]. In this work, time-domain temperature changes with and without the use of regulation by means of PID regulator have been compared. Results of the simulation show the usefulness of presented hybrid modelling method for the improvement of machine tool thermal behaviour.

1. INTRODUCTION

A significant problem in traditional machine tool modelling is a fact, that the real, mechatronic nature of an object is not taken into account, but only the pure mechanical behaviour is analysed [1,2]. Such simplification, influenced by the simplicity of use of finite element method, causes, that machine tool's mechatronical functions are omitted or simplificated, with the harm to the precision of reconstructing real model behaviour, considering real-time control.

The simulation of machine tool's behaviour, with the use of such modelling produces results excessively different from expected/real. It creates significant difficulties in achieving the precision of modelling and simulation, needed for improvement of precise machine tools, applied in high speed machining, and generally, high performance machining.

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Therefore, the improvement of modelling by its hybrid nature – understood by the integration of mechanical and mechatronic models – is significant for the development of scientific basis to the improvement of machine tools' exploitation operational precision.

2. CASE STUDY AND FEM MODEL ASSUMPTIONS

Thermal deformations, of machine tools, are usually a cause of most machining errors [3]. This fact creates the need to optimise thermal behaviour of machine tool, as well as the necessity to introduce compensation of resulting errors, although the effectiveness of compensation is often unsatisfactory. Such effectiveness strongly depends on the manner of machine deformations during work in long time cycles. Compensation procedures take into consideration the simplified mathematical model of errors caused by thermal deformations, and usually are based on neural networks or polynomial functions.

Their compliance with real errors depends on the precision of predicting the object's real behaviour during work. One of the methods for improving the degree of such behaviour's predictability, is minimisation, or even elimination of such deformations, which are difficult to compensate.

The solution proposed by authors, introduce the use of active cooling of, for example, the area of machine's guide, causing minimisation of thermal deformation of body, decreasing error of guide rectilinearity.

Analyses carried out by authors [4] show, that local heating of machine tool's body and the body's wall adjacent to guides, causes changes in machine geometry. This may cause, after relegation of spindle head into different work position, a rapid change of spindle tip position error (d*x*, d*y*), and more specifically the point on spindle axis. Fig. 1 shows such rapid increase in spindle end position error, taking place at time *t*=500min, when spindle head is moved by the value *A* along thermally deformed guides.

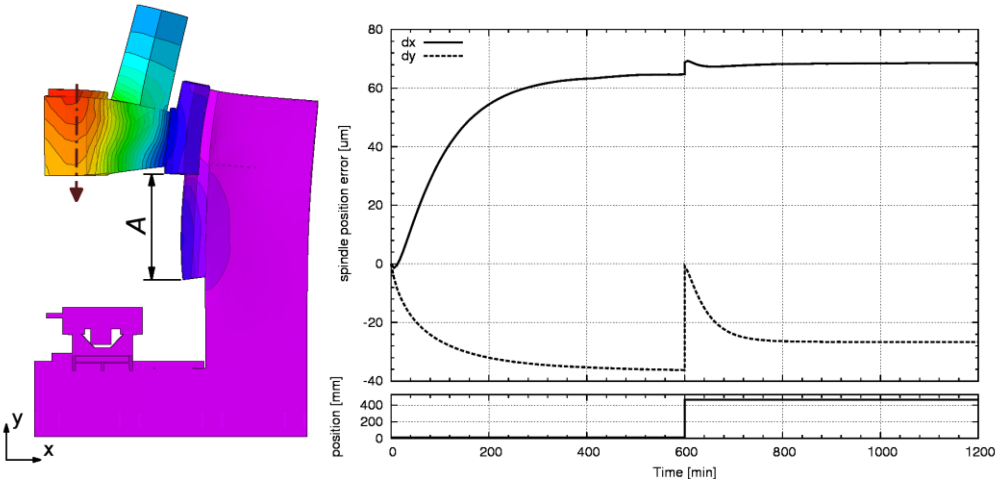

Fig. 1. Linear spindle tip position errors ZY versus time and mutual headstock/column position

In order to minimise the value of such error, an application of the active cooling system on spindle head guides has been suggested, and an analysis of such solution has been presented.

Since the goal of this work does not lie in presenting final technical solutions of the cooling system, but in assessing the capabilities of building a proper, virtual model of such solution, based on the finite element method, and its control, certain simplifications have been introduced. The most important simplification is substituting the model of a spindle "*c*", a transmission "*b*" and cooling element "*a*" with sources of heat. First two represent the work cycle and third one represents controllable power sink (Fig. 2).

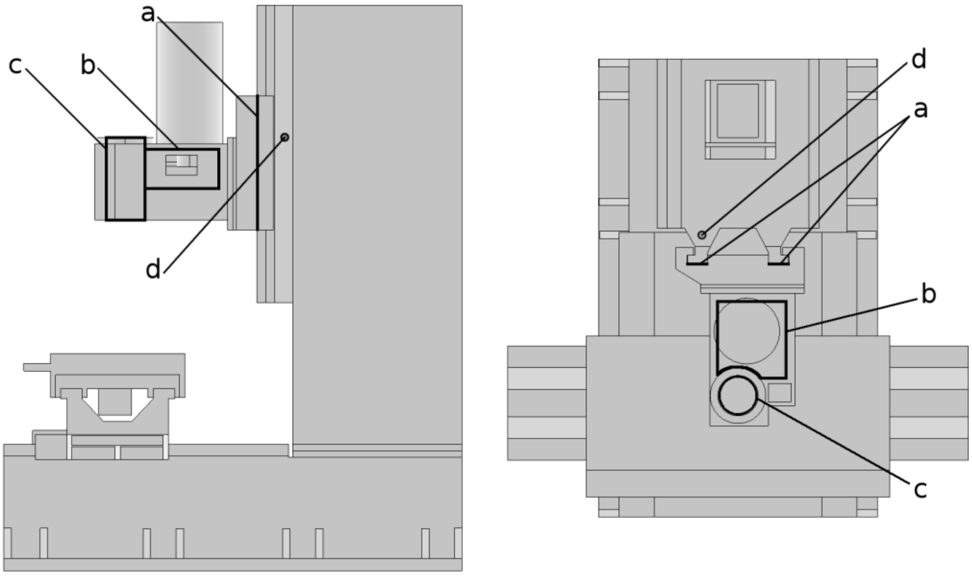

Fig. 2. The view of analysed machine tool model; a – power sink at the contact of guides, c – heat source placed at the mounting point of spindle, b – heat source caused by the operation of belt transmission,
d – temperature measurement point

The goal function is achieving constant temperature of measurement point "*d*", located on the wall of column cast, on the inner side. Based on preliminary numerical analyses of the model, location of measurement point "*d*" has been selected in such way, so the control process of its temperature creates as low column temperature gradients as possible. In real object, the goal function could be to minimise temperature differences present on the column, for example, levelling temperatures of points located on front and rear walls.

3. THE IDEA OF MECHATRONIC MODEL

Earlier mentioned approach to the modelling of physical systems, taking into account controlling and monitoring functions, is usually called mechatronic modelling. Such approach to the problem, apart from the knowledge about physical behaviour of system, also requires knowledge from many other areas, such as electronics, measurement techniques, control theory and information technology. It demands the ability to consider interdisciplinary elements of a system, which together with mechanical systems/units, create one, integrated system, where single components interact with each other. Fig. 3 shows basic elements of a mechatronic system.

The most common form of a mechatronic system model, is representing physical object, as well as electronic components, in mathematical expressions – usually in form of a transfer function. In case of simple mechanical systems, transfer function can be derived from differential equation of dynamics. But in case of complex objects, it is required to perform identification, which describes the behaviour of an object in form of a differential equation in a following form:

$$\sum_{n=0}^{N} A_n \frac{d^n Y}{dt^n} = \sum_{m=0}^{M} B_m \frac{d^m X}{dt^m} \tag{1}$$

where Y is an input variable, X – output variable, A_n and B_m are constant parameters of system's behaviour, whereas N and M independently define the order of a model. It should be pointed out, that many mechatronic objects have non-linear behaviour and cannot be described precisely by means of linear model. However, it is possible to define a specific range of input signals, for which the system can be represented, with acceptable precision, by linear model of certain order [5]. The process of choosing constants A_n i B_m is also called parameter estimation of a model.

Practical use of the modelling of mechatronic system requires skills in using different tools, such as FEM – for the analysis of system's physical behaviour (experimental data can be used instead), or computation programmes, such as MATLAB – to conduct identification and to model the control system.

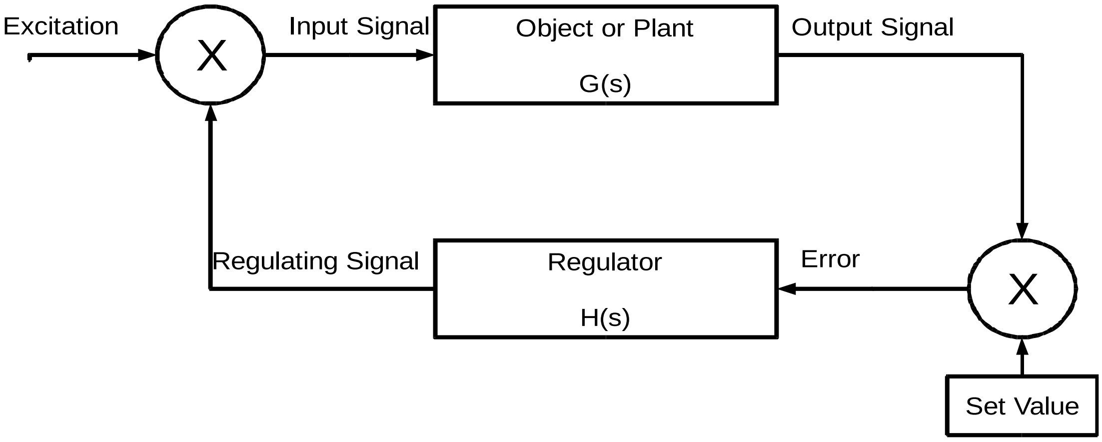

Fig. 3. Basic structure of mechatronic system

This paper presents the model of a system, which has the task of minimising thermal phenomena's influence on the precision of machine tool. System consists of FEM model (described in previous chapter) of machine tool's thermal behaviour, and mechatronic cooling system/unit. The innovation connected with this method consists in the exchange of information between single components of a model, during its computation cycle. Such procedure allows to omit identification of an object, making results more compliant with real behaviour, eliminating simplification connected with parameter estimation, and, by the use of special Solver, allows to take into account non-linear phenomena.

4. STRUCTURE AND MODEL OF THE COOLING CONTROL

Fig. 4 shows a model of cooling control module, built on the base of the structure of basic mechatronic system. This model includes:

- temperature sensor – modelled by reading temperature values of specific nodes from FEM result files, during FEM computations;
- cooling element (actuator) – additional heat sink placed in FEM model, introducing negative power flow in the system. The value of this power is acquired by the Solver from file written by MATLAB, before every iteration of computations;
- controller – PID regulator implemented in MATLAB, with experimentally adjusted regulation parameters.

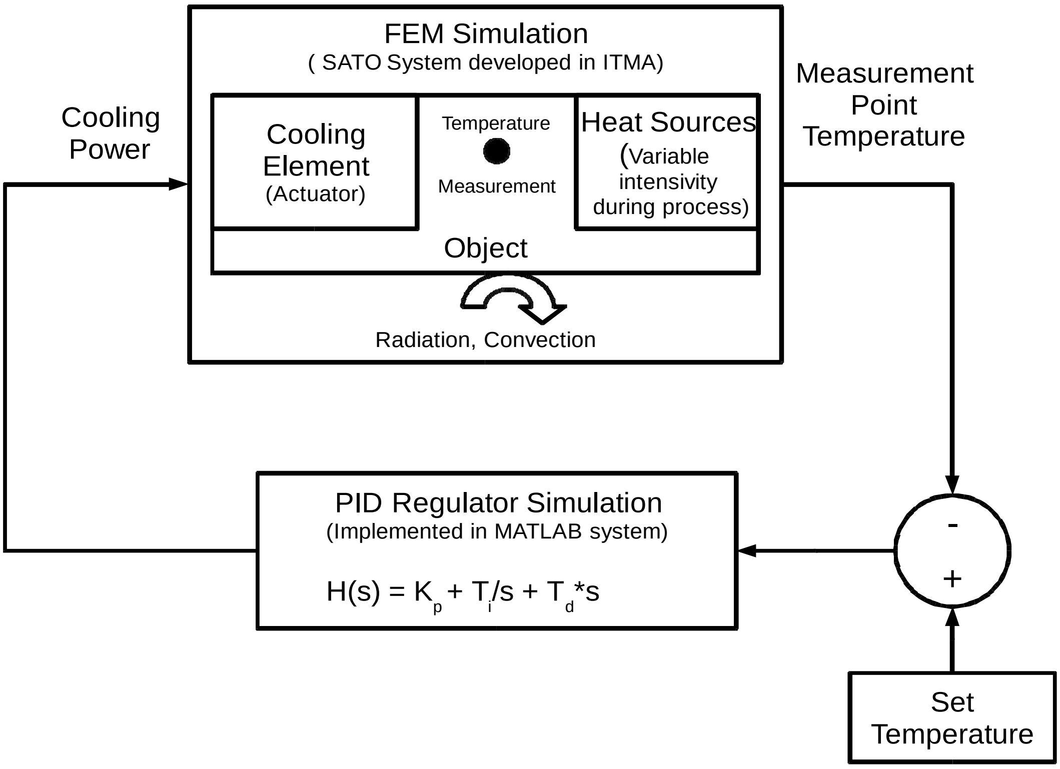

Fig. 4. Detailed model of mechatronic cooling control system

Considering the slow nature of changes in the state of an object, models of sensor and actuator do not consider their dynamic characteristics, such as delay or inertia. It should also be noted, that although during simulation the temperature in measurement point has been brought down to ambient temperature, it is possible for the regulator to work in follow-up mode, assuring uniform heating, following specific trajectory, to the optimal thermal balance temperature. Such operation would require building of knowledge base, containing information about these optimal conditions.

The exchange of information between the Solver of FEM model, and MATLAB, has been achieved by sharing data files over Ethernet network, allowing for both processes to run on separate computers, equipped with different operating systems.

5. PROCESS OF SIMULATION AND ANALYSIS OF RESULTS

Analyses with the use of described method have been conducted on a FEM model, built of 60297 tetra4 finite elements, and 20252 nodes. Boundary conditions include free heat exchange with environment through convection and radiation, as well as the load of chosen areas with heat power. Such cycle has been chosen to cause significant rise of column temperature in the region of contact with spindle head – as a result, thermal balance state has been approached. Analyses have been conducted in 1200-minute-long cycles, divided into three stages, 400-minute-long.

The power of heat sources (“*b*”, “*c*” on Fig. 2) have been declared at the level of: P_b=200W, P_c=120W during time range t=0-400min, P_b=0W; P_c=0W in time range t=400-800min; P_b=400W, P_c=240W in time range t=800-1200min.

Computations have been conducted with the use of iteration method, based on multiple execution of computation cycle, described in work [4]. Time step of 60s has been used, therefore execution of a Solver has taken place 1200 times for every computation variant. In every computation step, Proportional-Integral-Derivative (PID) regulator assessed the value of power P_a in such way, so the temperature of point “*d*” is kept constant (Fig. 2).

Fig. 5 shows a graphical representation of temperature distribution on the part of modelled machine tool, obtained after finishing the entire computation cycle for the case with disabled and enabled cooling system. While the value and distribution of temperatures in the region of spindle is similar in both cases, such distribution in the region of cooling component has been significantly changed. With disabled cooling (a), a clear impact of heat sources on the column temperature is observed, while the case with cooling enabled (b) shows, that the column temperature change along guides is unnoticeable. The whole column has approximately the same temperature.

In order to illustrate time-domain changes of model temperature, two measurement points, “*a*” and “*b*” have been selected (Fig. 6), located on outer surfaces of column and headstock cast, as well as measurement point “*d*”, located on inner surface of column cast.

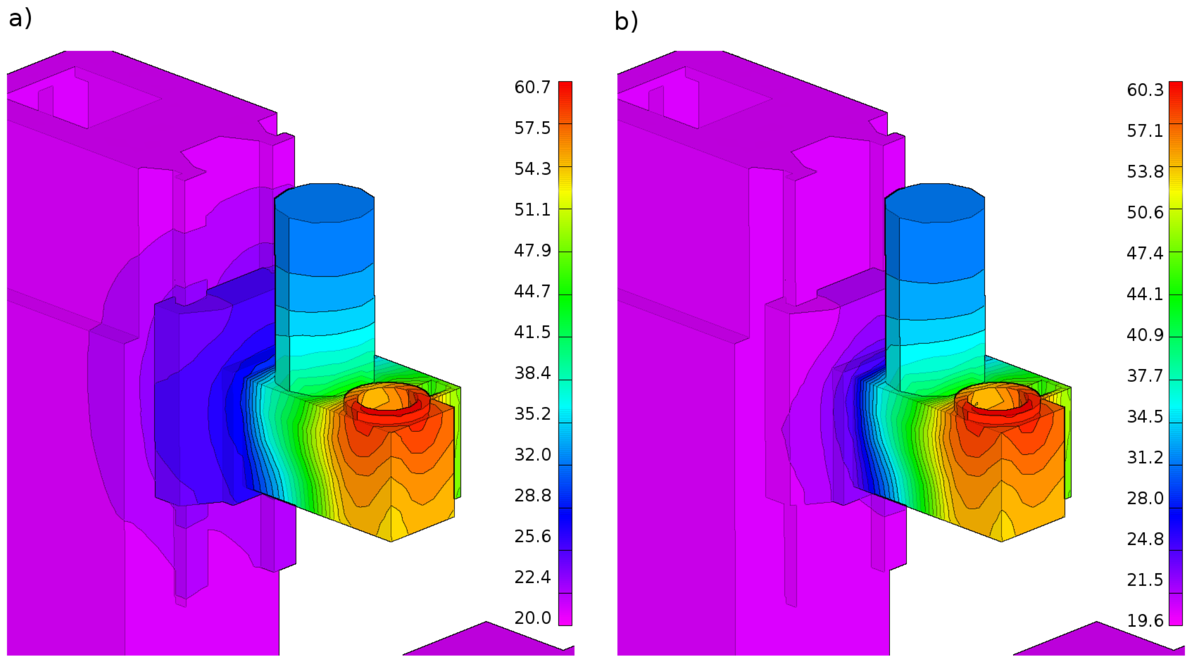

Fig. 5. Machine tool temperature field in time *t*=1200min; a – with cooling system disabled; b – with cooling system enabled

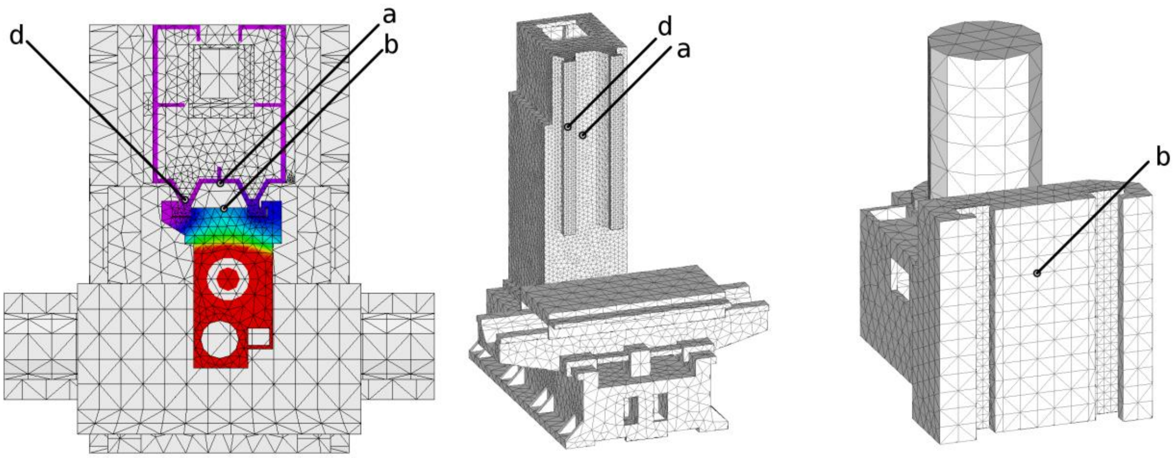

Fig. 6. Top view of machine tool FEM model with separated column and headstock. a,b,c – temperature measurement points

The comparison of time-domain temperature changes in specified points on the model, is shown on Fig. 7. Both analysis cycles, with cooling system disabled and enabled, have been included.

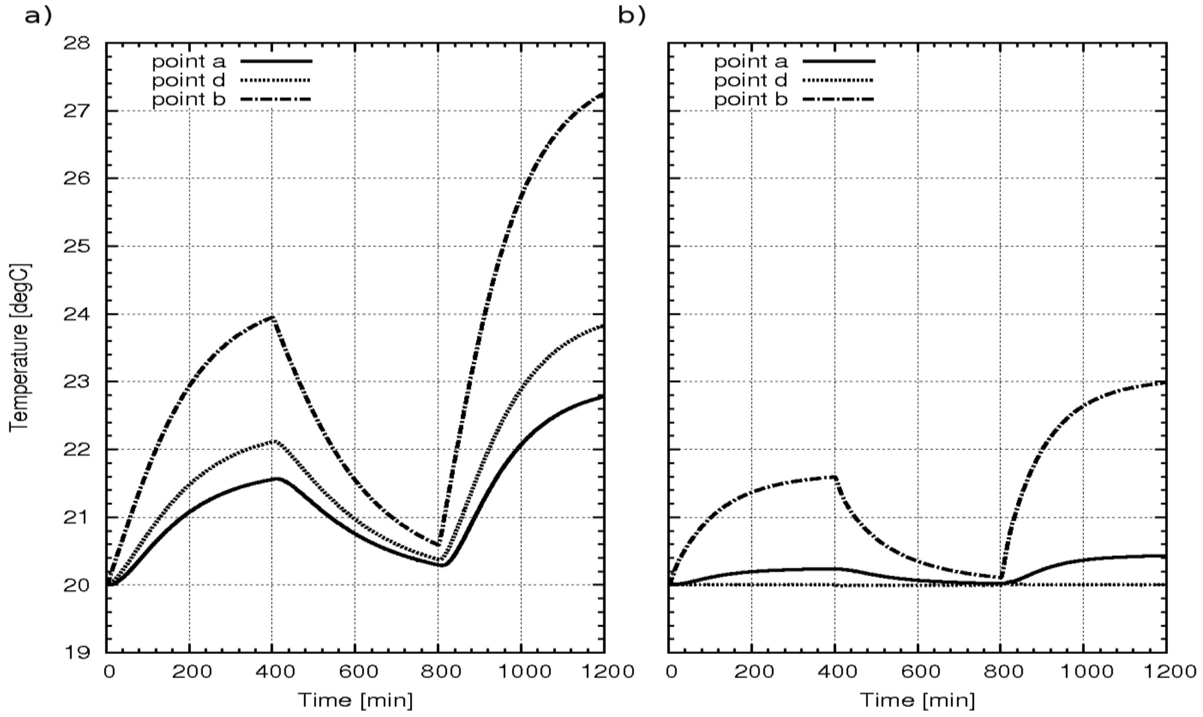

Fig. 7. Temperatures of chosen machine tool body points as functions of time, with active cooling system disabled (a) and enabled (b)

The reduction of temperatures, shown on Fig. 5b and 7b, has been achieved by the application of active cooling system, which in analysed case has been controlled by means of a PID regulator. The value of cooling power has been automatically chosen, based on actual, as well as previous values of measurement point "*d*" temperature. Error value (difference between actual and set temperature value) generates regulation signal by proportional term of a regulator. Derivative term adjusts regulation signal based on current derivative of temperature changes, causing the system to react to sudden temperature changes, and works as regulation oscillations damper. Integral term of a regulator eliminates steady-state error, by generating control signal based on the error integration value. Time-domain changes of temperature and cooling power have been presented on Fig. 8.

In modelled case, a regulator very precisely adjusts cooling power, keeping the temperature of measurement point at almost constant level. Compared to the rise of temperature, observed in analyses without heat sink, reaching up to 4°C, temperature fluctuations of about 0.05°C, obtained in a cycle with cooling, in real conditions would be impossible to measure. Therefore such system can be considered fully regulated. At the same time, used values of cooling power are at the level, which is possible to achieve with relative low energy consumption.

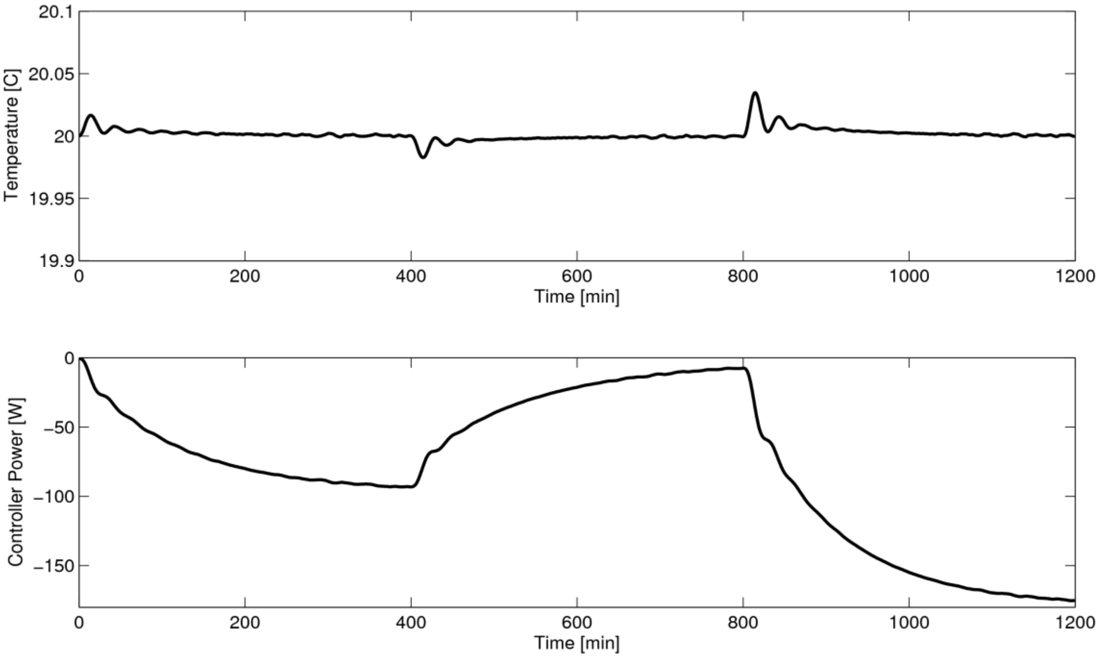

Fig. 8. Temperature of measurement point „d” as a function of time, together with corresponding power of the cooling system

6. GUIDELINES FOR APPLICATION OF THE METHOD IN WORKSHOP CONDITIONS

It should be mentioned, that in order to achieve desired cooling effect, in most cases it is required to feed the cooling system with coolant at the temperature lower than the set value. The following differential equation describes heat transfer by conduction:

$$\frac{\partial Q}{\partial t} = -k \oint_S \nabla T \cdot dS \, , \tag{2}$$

where Q is an amount of transferred heat, t – time, k – heat conduction coefficient, T – temperature and S – surface of heat transfer area. The equation shows, that the value of transferred heat is a linear function of temperature gradient ∇T. When feeding the coolant at the temperature higher or equal to the target temperature, heat flow stops, which makes the cooling effect at desired power level impossible. In such case, system regulation would be impossible.

Above analysis shows, that in order to achieve desired cooling system, it is required to use heat exchange element fed with coolant of lower temperature, for example, from cooling aggregate. The amount of received power would be regulated by means of controlling the temperature of coolant, and/or the amount of its flow. Also, a use of simply controllable heat pumps, exploiting the thermoelectric effect, would be possible, for example Peltier's diode, cooled by a coolant at any temperature.

To estimate the real precision of cooling, it is required to consider the simulation of efficient cooling design of heat exchangers, the complexity of required cooling aggregate, as well as a very precise modelling of machine tool thermal behaviour.

7. CONCLUDING REMARKS

The usability of mechatronical model, integrating mechanical (geometrical) structure of machine tool column with its cooling system and control, has been tested with a simple example of regulating the temperature changes in time of a chosen point on the column. Such simulation created the possibility of assessing the precision of temperature regulation. Improvement of such virtual experiment into complex, stereometric structures of heat exchanger and cooling generator (medium cooling device), will produce detailed parameters of their behaviour – relating to the specific task. Conducted experiment allowed to define cooling control parameters without the need of constructing prototypical physical model and work-consuming trials, which by nature produce very approximate guidelines for construction and operation of cooling system.

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