ANALIZA ROZWIĄZAŃ SPRZĘTOWYCH I PROGRAMOWYCH W FUNKCJI WIARYGODNOŚCI WYNIKÓW BADAŃ EKSPERYMENTALNYCH W TRAKCIE BADANIA SIŁ SKRAWANIA I TEMPERATURY W PROCESIE SKRAWANIA

ANALYSIS OF HARDWARE AND SOFTWARE SOLUTIONS IN FUNCTION OF THE RELIABILITY OF EXPERIMENTAL RESEARCH RESULTS DURING INVESTIGATION OF CUTTING FORCES AND TEMPERATURE IN THE CUTTING PROCESS

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W artykule opisano procedurę wspomagania komputerowego pomiaru i analizy sił skrawania i temperatury w procesie skrawania w obróbce toczenia, przy użyciu własnego rozwiązania sprzętowego oraz własnego oprogramowania. Wyznaczono, że są możliwe źródła błędów w proponowanych rozwiązaniach sprzętowych i programistycznych. Zaproponowano rozwiązania w celu zmniejszenia obszaru wyników pomiarów rozpraszania. Podano zalecenia dotyczące wprowadzania i obliczania niepewności wyników badań eksperymentalnych.

The paper describes a procedure for computer aided measurement and analysis of cutting forces and temperature in the cutting process by machining with turning, by using own software and hardware developed solutions. Denoted are possible sources of errors in the proposed software and hardware solutions. There are proposed solutions for reducing of the domain of the measurements results scattering. Given are recommendations for introduction and calculation of the uncertainty of the results of experimental researches.

Introduction

The research of physical phenomena in the cutting zone and technological effects in the surface layer during intensive machining conditions is mainly performed in two phases. In the first research phase, according to the investigation plan, determination of the values of investigated output quantities is carried out. The second phase is characterized by gaining mathematical models as a result of the certain constants or parameters determination that are in a function from the independent input variables (processing parameters) [1, 2, 3].

More and more often the research aim, besides the clear formulation of the research problem, the determination of the reliability of the gained results as output quantities of the research are included [4]. This implies to a parameter which can be included to the gained results, and to show to what extant the gain results can be trusted. Usually, this parameter that expresses the reliability of the gained results is called measurement uncertainty.

The lack of information about measurement uncertainty of a measured quantity value, in some cases may have a significant impact on the gained conclusions of the research, or to contribute to a wrong direction in further researches.
In order to contribute in this field, this paper analyzes the possible influence sources of the gained results reliability, during conducted experimental researches of forces and temperature in the cutting process by machining with turning.

In the implementation of experimental research phases, the experimenter is meeting activities related to selection of adequate measuring equipment for identifying the researched phenomenon. Adequate choice of methods for mathematical processing of the gained results and an adequate mathematical description of the researched phenomenon take place in determination of the reliability of the gained results.

Therefore, in this paper special attention is given to the scientific approach of methodology selection for solving such complex research problems as determination of the uncertainty of the measurement results.

Analysis of own software and hardware developed solutions

Experimental researches are often interdisciplinary characterized, connecting the mechanics, electronics and informatics. Information technology should provide a methodological approach while experiments conducting, adequate transmission of the signals and their processing, which ends with mathematical modeling of the researched phenomena. The same need to respond to a modern research requirements for creating open access to hardware and software modules. At the same time, computerization should provide simultaneous identification of several research phenomena (temperature and forces in the cutting process) in order to ensure identical conditions for adopting argumentative conclusions.

Figure 1 shows a scheme of a monitoring system that performs the determination of the temperature and the forces in the cutting process with turning. Computer aided measuring installation includes developed hardware and software solutions, which are a result of several years of joint research between the Faculty of Mechanical Engineering, Faculty of Electrical Engineering and Information Technologies in Skopje and the Institute of Mechanical Engineering and Automation of the Wroclaw University of Technology, Wroclaw, Poland [5, 6, 7]. Measuring installation includes two paths for measuring temperature in the cutting using the natural thermocouple method, integrated analog dynamometer for forces measuring, PC interface and software for PC. is 1 kHz for each channel separately. The developed software package for monitoring system support has the abbreviated code FORTMON (FORce & Temperature MONitoring). There is a section for graphic interpretation of forces and the ther-

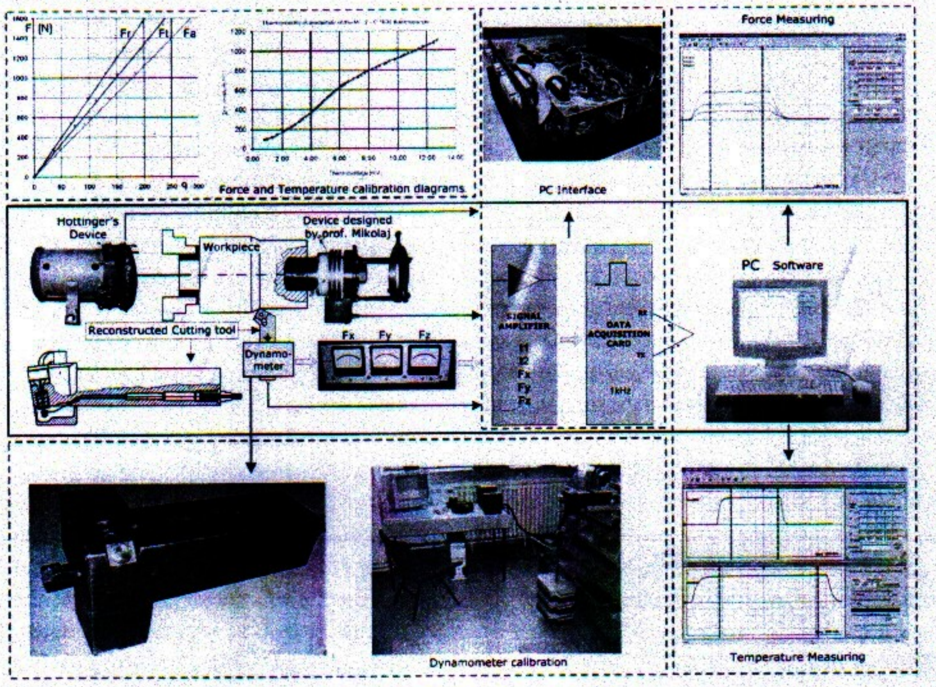

Fig. 1. Schematic representation of the experimental monitoring system setup

The integrated analog dynamometer's model is "Fisher messtechnik typ ef2 d3 nr 24570", consisted by cutting tool holder with inductive measuring cells for turning forces into electric signal. For temperature measuring the method of natural thermocouple workpiece-cutting tool is used. It is provided the generated thermo-voltage from the natural thermocouple to be transmitted at two paths. At the first path for the signal transmission of the workpiece, the special device [8] is been used, which can be applied in a case when the signal cannot be transmitted from the clamping head side through the main spindle. At the other path for transmission of workpiece the Hottinger's slip rings device it's been used and applied in a case when there is tube-shaped main spindle.

The interface between the signals source and the personal computer (PC) is composed of 5-channel amplifier for signals and acquisition card. The signal amplifier performs triple role as part of interface. It amplifies thermo-voltage generated from the natural thermocouple and the dynamometer signals to the required level. The second role of the amplifier is to provide galvanic separation of the electric circuits with the thermocouples, from the electric circuits which are consisted from data acquisition card and PC. The role of this galvanic is protection from any possible shocks that can damage this part of the measuring system. The third part is to remove the influence of the electric circuit consisted from acquisition card and PC of the electrical circuit with thermocouples and the dynamometer. Data acquisition card integrate microchip microcontroller type PIC 16F877 and supporting electrical components. The microcontroller has integrated 10-bit A/D converter and works with generator frequency of 20 MHz. The microcontrollers includes built-in module for serial synchronous and asynchronous communication in both directions with ability to easily adjust communication speed. For communication with PC a speed of 115.200 bps is being used. The sampling frequency

mo-voltage depending on time and a section containing dialogue window with many controls. It provides: real time - monitoring, software calibration, acquisition management, multitasking, resolution adjusting, many simultaneous analyzes, open source, data recording, settings recording, graphics export, selection of axes grid value and so on.

Calibration of the monitoring system for forces measurement is performed with applying load on the dynamometer in the direction of the specified component of the force, Figure 1. After each load change, the value indicated by the monitoring system was recorded. In this way, tables with corresponding values were created. The same are graphically analyzed and model that represents a relation between monitoring system reading and force was created. By using of this model into the software package, monitoring system readings can be expressed in force measurement units. Calibration of the monitoring system for temperature measuring is performed by determining of correlation between temperature and thermo-voltage with a special procedure [9]. The correlation is given by model (1). The thermoelectric characteristic of the natural thermocouple graphically is presented on the Figure 1.

$$T = 104{,}4 - 42{,}6u + 44{,}7u^2 - 4{,}9u^3 + 0{,}17u^4 \quad (1)$$

For experiment planning automation and results processing, until mathematical model creation the software tool *Matlab Model-Based Calibration Toolbox Version 1.1*, is used.

Possible errors sources into the experimental measuring system

Measuring uncertainty of gained results must adequately reflect the reliability of the gained results by involving all elements of the error sources in the measurement uncertainty budget.

Certain papers give recommendations for determining of errors that outcome from dynamometer calibration, but there is lack of estimations of the measurement uncertainty [4]. gives an example for evaluation of overall error during research of forces in the cutting process by machining with turning. It proposes inclusion of errors arising from calibration, but also proposes inclusion of errors arising from inaccurately adjustment of cutting parameters. The contribution of error arising from workpiece, tool and the machine are not taken into account in the analysis given in the paper but their presence is noted. It is important to conclude that it is necessary to include errors arising from data acquisition and processing system, i.e. the methodology used to obtain the mathematical model. The part of the measuring system that is designed for research of temperature in the cutting process additionally involves measurement uncertainty components that are connected to the selected method for determining the temperature and equipment used.

Figure 2 shows the possible sources of errors that should be taken into account when determining the magnitude of the forces and temperature in the cutting process.

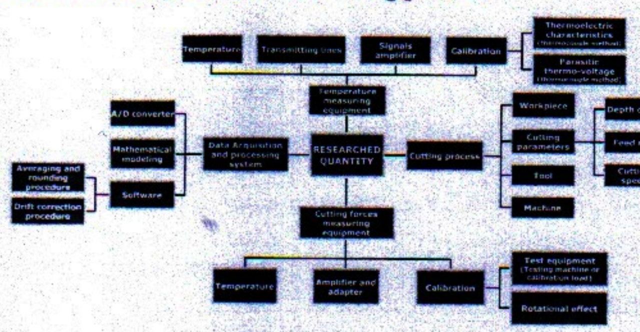

Fig. 2. The possible error sources during experimental research of physical phenomena in the cutting process

Recommendations for introducing and calculation of measuring results uncertainty

Components of standard uncertainty that outcome of error sources stated on Figure 2 could be evaluated by means of various procedures. Most often used are recommendations of GUM [10], however there are various studies that refer to determining uncertainty of the individual components [4, 11]. Uncertainty of gained results for forces and temperature in the cutting process is a sum of uncertainty components that result from the chain of realization of experimenter's experimental activities. Most often, uncertainty is expressed as a certain mathematical dependence related to cutting force or temperature. However often a mathematical dependence related to cutting parameters is suggested.

Contribution of force measuring equipment in evaluation of measuring uncertainty

Measuring uncertainty is recommended to be evaluated for each component individually taking into account that error sources can vary on each component.

Calibration procedure contribution

Dynamometer calibration is mostly performed by means of loading with known force.

Deviations from known force nominal value with which dynamometer is loaded contribute to measuring uncertainty, which outcomes from calibration procedure. Loading can be performed with a test machine or dumb-bells. If loading is performed with a test machine, standard uncertainty should be taken as it is defined for the test machine when calibrating it with a referenced standard for force. Uncertainty in cases of loading with dumb-bells with known mass will include the error gained by the procedure for determining real mass of applied dumb-bells. Researching equipment stated on Figure 1 is calibrated by means of dumb-bells with a mass determined by use of an electronic weighing scale whose uncertainty is $0,5 * 10^{-3}$ kg. Transferred into unit of force it would amount $4,9 * 10^{-3}$ N. Additionally, the environmental conditions are also taken into account when determining dumb-bells' mass.

When determining total uncertainty as a result of dynamometer calibration it is necessary to determine also the effect upon the uncertainty as result of the rotational effect. Many reasons are possible for this occurrence. In our case, the rotational effect occurs as a result of discrepancy between holder loading point at calibration and cutting plate tip. It could also occur as a result of discrepancy between dynamometer tool holder axis of symmetry and the direction of loading with known force.

Contribution of force signals adapter and amplifier

Force magnitude in the cutting process is determined experimentally by means of piezoelectric, inductive and tensiometric dynamometers [12]. In all these cases certain signal amplifier and adapter is used as link between dynamometer and acquisition system. Basically in question is an electronic unit consisting of a system of multiple operation amplifiers. Amplifiers with their characteristics contribute to significant errors in measurement system. This means that electronic components have certain deviation from nominal given linear amplification. Electronic components also have certain deviations that outcome as a result of temperature influence upon environment, as well as due to temperature influence on components in working conditions. Resistors which defines the nominal amplification of operational amplifiers have certain tolerance and also change their value dependent on environment temperature. Capacitors, which are used in some cases for signal smoothing prior acquisition, effect upon real signal value. Also, this whole electronic unit is in direct link with sensors, regardless whether these are piezoelectric or inductive, in a way that it is possible to decrease or increase signal value that outcomes of sensor. The reason for this is that they are not galvanic separated. Here should also add the effect that outcomes of temperature instability of sensor themselves, which are actually part of this electronic circuit. All this, finally, manifests as non-linearity of calibration line, which gives the dependence between acquisition system readings and known force with which it is loaded.

Improvements have to be made in all stated parts for the purpose of uncertainty decreasing, which outcome of this part of the measurement system.

Contribution of temperature measurement equipment in evaluation of measuring uncertainty

Wide scope of experimental methods exists for determining temperature in machining processes with material removal, thereof, various experimental research equipment, as well [13]. Methods for temperature determining by means of natural and artificial thermocouples are mostly applied.

Contribution of calibration procedure and system for signal transmitting

Procedure for determining thermo-electrical characteristic of thermocouples is experimentally performed and is very complex [9].

This characteristic is described by a mathematical dependence of higher degree. The contributions of the selection of number of terms in mathematical model, the effect of referenced temperature precision and selected calibration method are inevitable here. Generated thermo-voltage, by application of these methods, is transmitted onto the amplifier by means of a special device, reconstructed tool holder and conductors [14]. This is part of the measuring system where various effects upon signal could occur, which can contribute towards error occurrence. Effect is expected by the device, which transfers generated thermo-voltage from rotary workpiece onto measurement system. This device has a rotary and stationary part, while as the contact is accomplished with a slip rings. An occurrence of an artificial parasitic thermo-pair is possible at this spot as result of different materials and environment temperature on the contact. For the purpose of determining this effect, the measurement system is tested by application of an alternative method – application of Hottinger's slip rings device. Then, occurrence of eventual difference of temperature signals generated at equal machining conditions is determined. Additionally, it has to be considered the effect of the electromotive force that is being generating in the conductors through which the signal is transmitted, caused by the influence of lathe electro-motor work.

Contribution of amplifier on temperature signals

For the purpose a generated thermo-voltage to be brought in the domain of acquisition system, operational amplifiers are used, which, as in the system for adapting and amplifying of cutting force signals, contributes to the total measuring uncertainty. Since this electrical circuit has a very small internal electrical resistance, it is significant this amplifier to be galvanic separated from acquisition part. This is the only way to remove the effect of acquisition system to the circuit with a thermocouples, thereby reducing also one component of the measuring uncertainty. The whole objective here should be directed towards selection of a high-quality amplifier with min. dispersion of results that outcome of its non-linearity. An amplifier with non-linearity of 0,1% is selected in the interface of the monitoring system, described in this study. This precisely defines the value of standard uncertainty that outcomes of this part of measuring system.

Contribution of acquisition system and data processing

Contribution of A/D converter

A/D converters are basic elements of measuring chain that deliver measurement data in a form of digital information. In particular, their significance is very important because they provide automation of the measuring process by connecting the measuring equipment to computer or microcontroller, which results wit conditions for decreasing measuring uncertainty [15, 16]. Quality of output information depends initially of the input data precision and quality of A/D conversion expressed through parameter – uncertainty. This parameter, if analyzed as total uncertainty of A/D converter, also takes into account the effects of individual components onto A/D converter uncertainty. If uncertainties of individual components of A/D converter are known, as standard error, error at quantization, linear error, thermal noise and others, then all these participate in the determination of the summarized uncertainty [11]. In [11] for simplification purpose, determination of total error distribution is suggested by application of Monte Carlo's method. This proposition has an advantage; it includes the error caused by thermal noise, which is generated in A/D converter circuit. It is also concluded that distribution of total error gained in this way is most adequate, from practical point of view, since permits a relatively simple uncertainty calculation of A/D conversion result.

Software contribution

Software for processing and presentation of gained data has certain contribution on the measuring uncertainty. The contribution arises from the software procedures for averaging and rounding data, and by application of drift correction procedure.

Determination of standard uncertainty component, which outcomes of averaging and rounding certain numbers, depends on adopted adjustments in applied procedures. Therefore, it is necessary to use software that has open access to its components in these researches. On the contrary, uncertainty determining can not be performed in stated way. In some cases, due to certain reasons, certain mathematical apparatus could be implemented in the software, which significantly effects on measuring uncertainty, while experimenters are not familiar with it.

Drift correction procedure, since it represents a linear correction in terms of time, also implements error that needs to be determined in comparison with input data coming from acquisition system.

Contribution of mathematical modeling

Gained measurement data, considered as points of experimental plan, are used in the regression analysis for mathematical modeling of researched phenomena. Many authors for describing physical phenomena in cutting process suggest power functions. A dependence between physical phenomena during the cutting process and cutting parameters is described by verified power mathematical models (2) [17, 18].

$$\varphi = C \cdot a^{x} \cdot f^{y} \cdot v^{z} \tag{2}$$

Expression φ represents researched quantity, component of cutting force or temperature, represents cutting depth, while f is the feed and v is the cutting speed. Degrees are presented as x, y, z. During logarithmic data transformation for purpose of gaining mathematical model in a given form, certain error occurs [19]. In addition, the selection of experimental plan, full factorial or replicas, results with certain difference in determined degrees [12]. Conclusion is that expression (2) should be more precisely stated in following form:

$$\varphi = (C \pm \Delta c) \cdot a^{x \pm \Delta x} \cdot f^{y \pm \Delta y} \cdot v^{z \pm \Delta x} \tag{3}$$

where Δc is possible deviation of constant and Δx, Δy, Δz are possible deviations of degrees, in dependence of the error value that can outcome during mathematical modeling process.

Therefore, determination of standard uncertainty component that outcomes of mathematical modeling is also necessary.

Contribution of machining process

It is well familiar that parameters applied in machining process as cutting speed, feed and cutting depth often deviate from nominally given values. Thereof it is necessary to include uncertainty component that describes this error. For decreasing these effects upon uncertainty value, additional measurements are recommended on cutting depth, feed and cutting speed. In this way measuring uncertainty is going to be based on these measurements, not on programmed machine values. This is very vital if it is taken into account that even 50% of results' dispersion during research of forces during cutting is due to errors that outcome of machining process [4].

In some cases, uncertainty components that outcome of workpiece, machine and cutting tool could be reduced and or become insignificant. So, for an instance, uniformity of machined material hardness can be achieved if the strain-hardened shoulder was removed prior researches.

Conclusions

Analysis of available literature for developing experimental measurement equipment for researching physical phenomena in cutting process, as well as experiences gained in phases of creating hardware and software solutions within monitoring system for force and temperature measurements in cutting process by machining with turning, provide following conclusions to be reached:

- Developed hardware and software solutions applied in experimental measurement equipment create pre-conditions for gaining knowledge and experience for the effect of fitted components upon validity of measured result, as well as adequate mathematical description of researched phenomena.
- The effect of used component upon measured result could be also quantitatively expressed by adequate selection of components with various characteristics fitted in experimental measurement equipment.
- Opened access to hardware and software solutions provides recognition and removal of systematic errors that occur in measurement system, which is not the case for ready commercial solutions.
- Reduction of gained results' dispersion interval when performing experimental researches represents a complex objective that is expected to be achieved by analysis of all actions done by experimenter (researched problem description, selection of correspondent methods and measurement techniques, selection of function form and defining input and output, analysis and defining of experimental hyperspace, experiment planning, projecting and installing in measurement systems, experiment realization, statistical data processing and mathematical description of researched phenomena, mathematical model verification and actions linked with it), through finding weak technological solutions and suggesting solutions for its improvement.
- Future scientific-researching actions of authors are directed towards further precision of developed methods for quantitative determining of total uncertainty.

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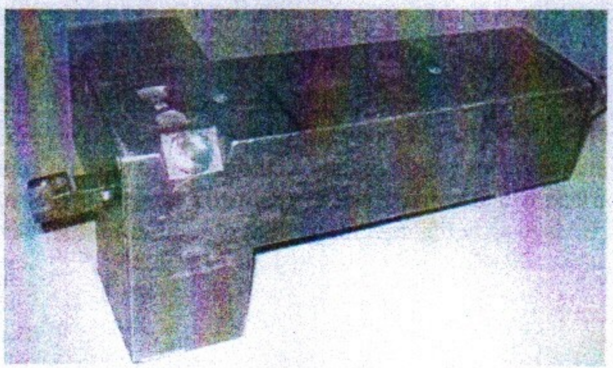

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SPIS TREŚCI / CONTENTS

Piotr Danielczyk, Ireneusz Wróbel — 7 — **Analiza drgań zespołu klimatyzatora**
Vibration analysis of an air-conditioner unit

Ludwik Kania, Szczepan Śpiewak — 10 — **Nośność statyczna łożysk wieńcowych podwójnych z uwzględnieniem sił promieniowych obciążających łożysko**
The static carrying capacity of twin slewing bearings with the considering of radial forces

Marek Krynke — 16 — **Numeryczna identyfikacja kątów działania elementów tocznych w łożysku wieńcowym kulkowym jednorzędowym**
The numerical identification of the rolling elements contact angles in the single-row slewing ball bearing

Grzegorz Krzesiński, Piotr Marek, Tomasz Zagrajek, Paweł Borkowski — 21 — **Modelowanie metodą elementów skończonych połączeń centralna struktura nośna – cewki w reaktorze syntezy jądrowej Wendelstein 7X**
Fe modelling of central support elements in Wendelstein 7X fusion reactor

Monika Polak-Micewicz, Tadeusz Łagoda — 25 — **Wyznaczanie naprężeń i odkształceń w krytycznych punktach spągnicy**
Determination of stresses and strains in the critical points of the base

Grzegorz Sławiński, Elżbieta Szymczyk, Tadeusz Niezgoda, Jerzy Jachimowicz — 29 — **Wpływ luzów geometrycznych na stan naprężenia w otoczeniu nitu grzybkowego**
Influence of geometrical imperfection on residual stress fields around the mushroom rivet

Piotr Sokolski — 33 — **Analiza wytrzymałości ogniw gąsienicowych wielonaczyniowych koparek kołowych**
Strength analysis of caterpillar links of bucket wheel excavators

Piotr Sokolski — 36 — **Naciski jako podstawa oceny gąsienicowych mechanizmów jazdy maszyn roboczych**
Base compression as a foundation of evaluation of caterpillar carriages in working machines

Jacek Stadnicki, Zbigniew Tokarz — 39 — **Mezoskalowy model MES do obliczania odkształceń konstrukcji z kompozytów warstwowych**
Mesoscale FEM model for calculating deformations of laminate composite constructions