AN APPROACH FOR MEASUREMENT UNCERTAINTY EVALUATION OF CUTTING FORCE IN MACHINING BY TURNING

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1. INTRODUCTION

The importance to associate uncertainty parameter to the result of cutting force measurement is stressed in many machining studies [1, 2]. The other important matter concerning such uncertainty parameter is its reliability. Under or over estimation of the measurement uncertainty can occur during the process of calculation of the uncertainty budget. This is result of the complexity of the measurement process. It is common practice to include the calibration uncertainty of the dynamometer, while there is lack of examples of including the cutting process errors in the uncertainty budget. If we consider that cutting force value can be used for further mathematical modeling of the cutting process and it will be related to the cutting process parameters, than it is very important to account all possible deviations (errors) of cutting parameters from programmed values by including corresponding uncertainty factor.

Measurement uncertainty during cutting force measurement is specific for certain measurement experimental setup and applied identification methodology, and therefore it will be significant for metrological community to have outlook in different approaches. This paper presents an approach which is developed during experimental research of physical phenomena in the machining process by turning on the Faculty of

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Mechanical engineering in Skopje, Macedonia. Estimation of the measurement uncertainty for single cutting force measurement is in the spirit of GUF (GUM [3] uncertainty framework). The analysis accounts both calibration and cutting process contributors into the uncertainty budget.

2. EXPERIMENTAL INVESTIGATION

Measurement of the cutting force is carried on by using Computer aided system for investigation of cutting forces and temperature in turning, figure 1. The monitoring system is developed on the Faculty of Mechanical engineering in Skopje [4]. In the example presented tangential cutting force component is measured. The experimental setup and the cutting process have the features showed in table 1.

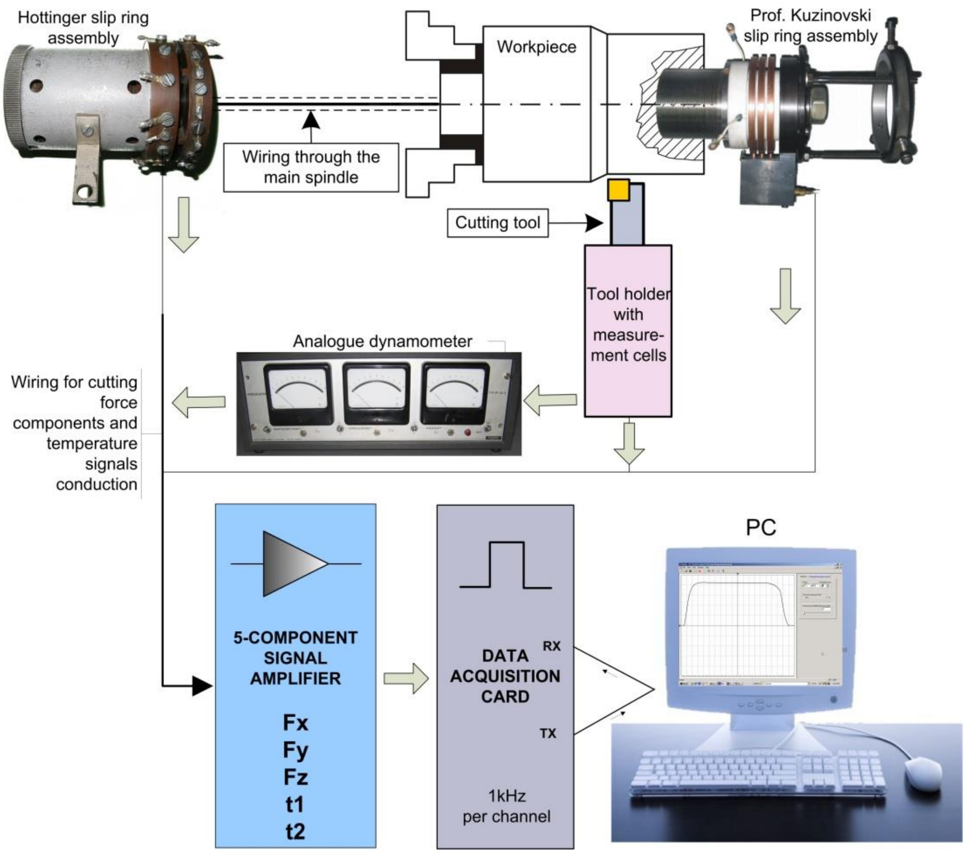

Figure 1. Computer aided system for investigation of cutting forces and temperature in turning [4]

Table 1. Experiment features

Workpiece material	*Carbon steel: DIN C55, Diameter=100 mm*
Lathe (conventional)	*Prvomajska, Niles*
Cutting tool holder	*KENNAMETAL, Kenloc MSSNR2525M12 25x25 mm adjusted to 18x18 mm*
Cutting insert	*HERTEL, SNGN* 120704, *mixed ceramics MC2* (Al_2O_3+TiC)
Cutting tool stereometry	$\chi=45°, \chi_1=45°, \lambda=-8°, \gamma=0°, \alpha=10°$, $r_\varepsilon=0{,}4\,mm$
Dynamometer	*Inductive cells based- FISHER MESSTECHNIK TYP EF2 D3 NR 24570*
Cutting process parameters	*Cutting depth* $a_p=0{,}5\,mm$; *Feed rate* $f=0{,}224\,mm/2\pi rad$; *Cutting speed* $v_c=52{,}8\,m/min$;
Measurement characteristics	*Acquisition time 3,9* s, *Sampling frequency* 1kHz, *real time*

Procedure of identification of the contributing factors is performed by using the Ishikawa diagram, figure 2.

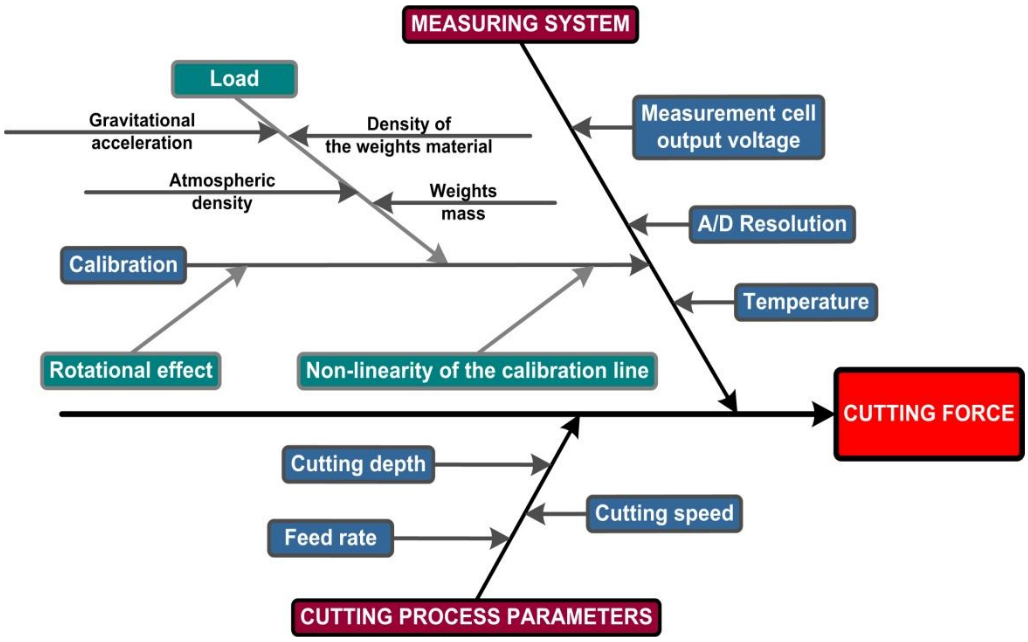

Figure 2. Ishikawa diagram of cutting force measurement uncertainty contributors

Based on cause-effect analysis a mathematical model for propagation of the combined measuring uncertainty of the tangential cutting force component is given by (1),

$$F_t = k_{t-r}\left(v_r + \delta r_r + \delta G_r + \delta t_r + \delta z\right) + k_{t-a}\left(v_a + \delta r_a + \delta G_a + \delta t_a + \delta z\right) + \\ + k_{t-t}\left(v_t + \delta r_t + \delta G_t + \delta t_t + \delta z\right) + \delta a + \delta f + \delta v \qquad (1)$$

where: i–index, $i=r, a, t$; r-radial cutting direction, a-axial cutting direction, t-tangential cutting direction;

F_t – tangential cutting force component;

k_{t-i} – calibration matrix coefficients for tangential direction, $i=r, a, t$;

v_i – output voltage of the dynamometer amplifier, $i=r, a, t$;

δr_i – rotational effect uncertainty contribution, $i=r, a, t$;

δG_i – calibration load uncertainty contribution, $i=r, a, t$;

δt_i – temperature contribution, $i=r, a, t$;

δz – acquisition circuit resolution uncertainty contribution;

$\delta a, \delta f, \delta v,$ – cutting parameters uncertainty contributions, a_p - depth of cut, f - feed rate, v_c - cutting speed.

Efforts were made in direction of excluding contributors from the tool, workpiece and the machine.

2.1. CALIBRATION CONTRIBUTION

The calibration line has been modeled by least squares method and linear regression model was adopted. Calibration load was applied by weights, figure 3.

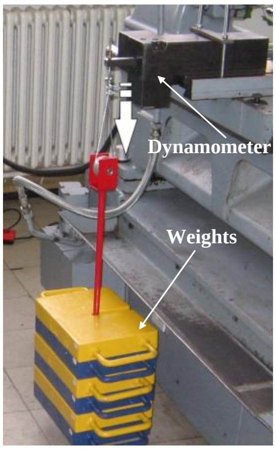

Figure 3. Calibration of system for cutting force measurement

After calculation the coefficients k_{t-i} were obtained and they are characterized by their normal distribution with mean and standard uncertainty presented in the table 2. Distribution of the coefficients is measure of possible deviation from the linearity of the calibration line.

In order to avoid bigger values for load uncertainty that can occur from available testing machines a different approach is adopted and deadweight generated force is used. The downward force exerted on a static deadweight is given by (2) where *G* is the applied force in N, m is the mass of the weight in kg, g is the gravitational acceleration in m/s^2, ρ_a is the atmospheric density at the location of the weight, and ρ_m is the density of the weight in the same units as ρ_a [5, 6]. The uncertainty in this force δG_i is dependent upon the uncertainties in the measured values of the mass, gravitational acceleration, and the ratio of the air and weight densities, which are calculated respectively. δG_i calculated and converted in V by using the corresponding calibration lines are presented in table 2.

$$G = m \cdot g \cdot \left(1 - \frac{\rho_a}{\rho_m} \right) \tag{2}$$

The rotational uncertainty δr_i applies for the effect from possible difference in the inclination of the axes of the applied calibration force and the dynamometer axes [7]. Calculated values are converted in V by using the corresponding calibration lines and presented in table 2.

2.2. MEASURING SYSTEM UNCERTAINTY

Beside the calibration uncertainty which is described above, other contributors from the measuring system are: v_i - measurement cells mean output voltages, δz - acquisition circuit resolution and δt_i - temperature. v_i mean and standard uncertainty is estimated from obtained data from the acquisition of one measurement. Values for all three cutting force components are shown in table 2.

The acquisition circuit resolution uncertainty contribution is predetermined by the size of its smallest division. It is calculated within the voltage domain of 5V and the 10-bit conversion possibility and shown in table 2.

The calculated error which outcomes from possible environment temperature influence on the measured signals is observed in the amplifier circuit. The cascade amplifier was made by TL084 operational amplifiers. Using the manufacturer's datasheet, the overall temperature uncertainty was calculated and included in the table 2.

Table 2. Budget of the measurement uncertainty for tangential cutting force component

Quantity	Value	Units	Standard uncertainty u_i	Sensitivity coefficient c_i	Uncertainty contribution $c_i u_i$ [N]	Index %	Distribution
k_{t-r}	5,242	N/V	2,195	0,281	0,617	0,3	Gaussian
v_r	0,280502	V	10,79 x 10^{-5}	5,24	56,538 x 10^{-5}	0,0	Gaussian
δr_r	0,0	V	0,0849	5,24	0,445	0,2	U-Quadratic
δG_r	0,0	V	5,2 x 10^{-7}	5,24	2,7 x 10^{-6}	0,0	Gaussian
δt_r	0,0	V	8,66 x 10^{-4}	5,24	0,00454	0,0	Uniform
δz	0,0	V	0,00141	5,24	0,00739	0,0	Uniform
k_{t-a}	-2,368	N/V	0,296	0,209	0,0619	0,0	Gaussian
v_a	0,208739	V	9,857 x 10^{-5}	-2,37	-2,3361 x 10^{-4}	0,0	Gaussian
δr_a	0,0	V	0,00350	-2,37	-0,00829	0,0	U-Quadratic
δG_a	0,0	V	3 x 10^{-8}	-2,37	-7 x 10^{-8}	0,0	Gaussian
δt_a	0,0	V	8,66 x 10^{-4}	-2,37	-0,00205	0,0	Uniform
δz	0,0	V	0,00141	-2,37	-0,00334	0,0	Uniform
k_{t-t}	619,783	N/V	3,486	0,448	1,562	2,1	Gaussian
v_t	0,44823	V	1,231 x 10^{-4}	619,78	0,0763	0,0	Gaussian
δr_t	0,0	V	0,00350	619,78	2,169	4,0	U-Quadratic
δG_t	0,0	V	10,81 x 10^{-6}	619,78	0,00670	0,0	Gaussian
δt_t	0,0	V	8,66 x 10^{-4}	619,78	0,537	0,2	Uniform
δz	0,0	V	0,00141	619,78	0,874	0,7	Uniform
δa	0,0	N	10,200	1,0	10,200	88,7	Gaussian
δf	0,0	N	2,080	1,0	2,080	3,7	Gaussian
δv	0,0	N	0,272	1,0	0,272	0,1	Gaussian
F_t	278,782	N	$u_C = 10{,}828$				Gaussian

2.3. CUTTING PROCESS UNCERTAINTY

Contribution from the cutting depth variation is estimated from five measured values of the workpiece diameter before and after the cutting pass. Dispersion of the differences between the programmed and measured cutting depth is considered like a measure for the uncertainty contribution from this error. The value of calculated standard uncertainty is 14,43 µm. This value is converted in N by using already modeled linear regression between the tangential force and cutting depth (3).

$$F_t = 708{,}25 \cdot a \tag{3}$$

Cutting speed contribution is estimated from data obtained from rotational speed meter. Considering rotational speed meter accuracy and workpiece diameter, estimated standard uncertainty is 0,1732 m/min. This value is converted in N by using already modeled linear regression between the tangential force and cutting speed (4).

$$F_t = 600{,}48 - 1{,}5715 \cdot v \qquad (4)$$

Feed rate uncertainty contribution is considered as very specific for determining. In this research it was decided to estimate it through analysis of machined surface 2D roughness parameter, which was taken as appropriate depicturing of the tool tip movement. The parameter of our interest was PS_m - mean width of the profile elements of the primary profile. Standard uncertainty is estimated to 0,0014 mm and it is converted in N by using already modeled linear regression between the tangential force and feed rate (5).

$$F_t = 86{,}867 + 1387{,}8 \cdot f \qquad (5)$$

2.4. CUTTING FORCE UNCERTAINTY BUDGET

After determining the standard uncertainties of all included parameters, sensitivity coefficients were calculated and combined standard uncertainty of the tangential cutting force was propagated by using the GUM method, table 2. Expanded uncertainty for coverage factor 2 and for 95% confidence interval will be 21,7 N. The column *Index* in table 2 is showing the contribution size of the particular factors. From preliminary analysis we can say that contributions which come from noticed correlation from other axes are not significant. This can lead to further recommendation not to consider these influences in further researches. Very significant is the choice to decrease the uncertainty from the calibration load by selecting calibration to be made by deadweights. That allows the uncertainty index to be distributed to factors on which we must pay further attention and to find a way to lower their influence. The acquisition circuit resolution uncertainty can be eliminated by simple selection of more accurate A/D convertor which are now widely available. In order to lower the non-linearity of the calibration lines which are presented trough calibration coefficients deviation, efforts must be made in direction of providing more reliable or accurate dynamometer and amplifier, but to consider if this improvement is justified because we have significantly bigger uncertainty which arise from the cutting process. In that spirit maybe attention should be directed towards the lowering the rotational effect contribution. Cutting process contributions are the most important and the biggest influence will outcome from the feed rate or the cutting depth depending from selected cutting parameters, tool, workpiece and other conditions. By our opinion many efforts must be done to lower these contributions.

3. CONCLUSIONS

In this study it is shown an example of experimental measurement of cutting force during machining with turning and estimating of the associated parameter which describes the measurement uncertainty. It is proposed a tool for identification of the influencing contributors and it is developed a mathematical model for propagation of the measurement uncertainty including factors from the measuring system and factors from the cutting process itself. It can be concluded that main source of uncertainty is coming from the cutting process. Further recommendations are in direction of lowering these significant errors more than focusing on improvement of the force measuring system. After depicturing the errors in the form of table 2 our opinion is that this method is essential for researches of cutting force and without it results can not be considered as complete. Uncertainty parameter makes measurement result to have reliable interpretation.

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