SYMULACJE MONTE CARLO PODCZAS VALIDACJI NIEPEWNOŚCI POMIARÓW SIŁY SKRAWANIA W TOCZENIU

MONTE CARLO SIMULATIONS IN VALIDATION OF MEASUREMENT UNCERTAINTY OF CUTTING FORCE DURING MACHINING BY TURNING

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W artykule przedstawiono wyniki walidacji niepewności pomiarów siły skrawania z zastosowaniem symulacji Monte Carlo GUM z uzupełnieniem 1. Obliczenia realizowano na przykładzie wyników uzyskanych z badań doświadczalnych podczas pomiaru siły skrawania w warunkach obróbki toczeniem. W badaniach zastosowano wsparty komputerowo system pomiarowy. Przedstawione wyniki badań analitycznych oraz wynikające z nich wnioski dotyczące walidacji niepewności pomiarowej dokonano w oparciu o metody numeryczne.

This paper presents validation results of measurement uncertainty of cutting force by using Monte Carlo Simulations according to GUM Supplement 1. The calculations were performed over experimental results obtained by computer aided measuring system in measuring of cutting force during machining by turning. There are given conclusions for a need of validation of measurement uncertainty in this field by using a numerical method.

Introduction

The principles of the GUM [1] for evaluating and expressing uncertainty in measurement are very well accepted in the metrological community. Numerical approach for carrying out the calculations required for evaluation of measurement uncertainty is given in the Supplement 1 to the GUM [2]. GUM uncertainty framework (GUF) is based on the law of propagation of uncertainty and on the characterization of the quantities measured by means of either a Gaussian distribution or a t-distribution, which allows measurement uncertainty to be delimited by means of a confidence interval. To determine this confidence interval GUF may only be applied if two conditions are met: firstly, linear dependence must exist between the measurand and the influence quantities of the measurement process (If the mathematical model of measurement is not linear, it is linearized based on the first order Taylor series approximation.); and secondly, the application of the central limit theorem must be justifiable. The proposed numerical approach, by using Monte Carlo Simulations (MCS), is a practical alternative to the GUM uncertainty framework and tool for validation of applied GUM approach. Such alternative is proposed due to the following possibilities: firstly, the estimate of the output quantity and the associated standard uncertainty provided by the GUM uncertainty framework might be unreliable as result of applied linearization of the mathematical model of measurement; and secondly, coverage intervals might be unrealistic as probability density function (PDF) for the output quantity departs appreciably from a Gaussian distribution or a scaled and shifted t-distribution [2]. Using the MCS as validation tool during measuring uncertainty assessment within GUM uncertainty framework should be optimal solution which can benefit with avoiding of both methods' disadvantages.

Up to now many research efforts have been directed towards the monitoring of cutting force during machining by turning. During this identification process a variety of force sensors and signals processing methods have been employed which differently contribute to the budget of the associated measurement uncertainty. Further, values of the measurand are intended often to be used for mathematical modeling of the cutting process or it should be reported under which conditions (process parameters) they are measured. For example, while modeling the functional relationship between the measurand and the cutting parameters, a need arises to include the contribution of the cutting process errors into the uncertainty budget of the measurand. That makes determining of the measuring uncertainty in the considered field to be a very complex process and, because of that, we are facing with many published results of cutting force measurement without associated measurement uncertainty. From our experience we can also stress on the importance of knowing the different contributions into the overall budget of the measurement uncertainty, which can lead to optimization of the measurement process. However there are new trends in this field and papers published that present developed mathematical models for cutting force uncertainty including cutting process parameters [3, 4]. Analysis of the proposed models for cutting force uncertainty shows that the list of contributing input parameters is not small and that probability density functions which describe contributing input parameters can be of any type, not only a Gaussian distribution or a t-distribution. This imposes doubt in the expected result and in the applied GUM uncertainty framework and proposes applying the MCS method in the spirit of Supplement 1 to GUM, which is the scope of this paper.

Research scope

This research begins with development of measurement uncertainty mathematical model for measurement carried on by computer aided cutting force monitoring system. Developed model can be unique for the certain measuring system but also it can be applied for similar ones or to be a base for comparison with others. Further the GUF measurement uncertainty budget for single force measurement will show the amount of influence of the contributors, will give picture about authors experience to lower the certain errors of the measuring system and will discover week spots in the measurement chain. Additionally it can be seen implementation of MCS method for validation of the applied GUF method. Also it will be presented the significance of validation which detects a simple intentional change of some parameter which disrupt GUM application conditions, previously described (as it can exist in different experimental setup or measurement), by giving negative validation result.

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 [5]. In the certain example tangential cutting force component is measured. The experimental setup and the cutting process have the features showed in table 1.

Developed mathematical model for propagation of the combined measuring uncertainty of the tangential cutting force component is given with (1).

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

Tab. 1. Experiment features

Workpiece material	Carbon steel: DIN C55
Lathe	Prvomajska, Niles
Cutting tool holder	KENNAMETAL, Kenloc MSSNR2525M12 25x25 mm adjust to 18x18 mm
Cutting insert	HERTEL, SNGN 120704, mixed ceramics MC2 (Al2O3+TiC)
Cutting tool stereometry	$\chi = 45°$, $\chi_1 = 45°$, $\lambda = -8°$, $\gamma = 0°$, $\alpha = 10°$, $r_e = 0{,}4$ m
Cutting process parameters	Cutting depth $a = 0{,}5$ m, feed rate $f = 0{,}224$ mm/2πrad, cutting speed $v = 52{,}8$ m/min
Measurement characteristics	Acquisition time 3,9 s, Sampling frequency 1kHz

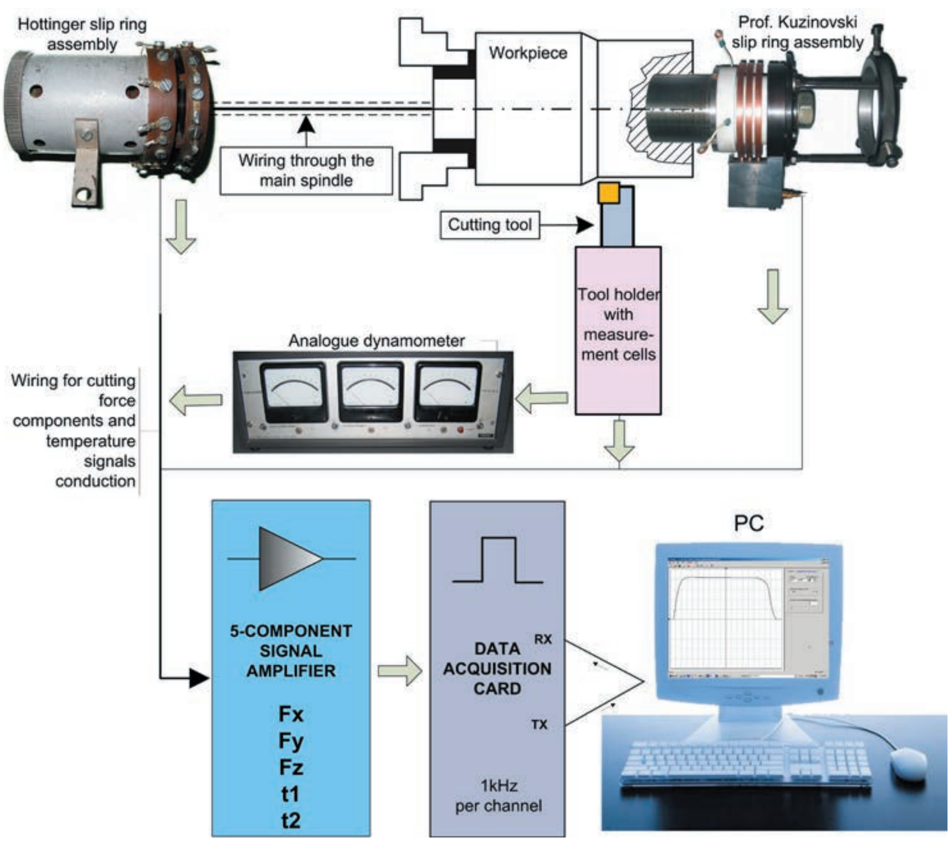


Fig. 1. Computer aided system for investigation of cutting forces and temperature in turning [5]

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

Quantity	Value	Units	Standard uncertainty u_C	Sensitivity coefficient c_i	Uncertainty contribution $c_i u_i$ [N]	Index %	Distribution
k_{t-r}	5,241922	N/V	2,19519500	0,28	0,61465460	0,32	Gaussian
v_r	0,28050173	V	0,00010790	5,24	0,00056538	0,00	Gaussian
δr_r	0	V	0,08485281	5,24	0,44462874	0,17	U-Quadratic
δG_r	0	V	0,00000052	5,24	0,00000270	0,00	Gaussian
δt_r	0	V	0,00086600	5,24	0,00453784	0,00	Uniform
δz	0	V	0,00141000	5,24	0,00738840	0,00	Uniform
k_{t-a}	-2,367594	N/V	0,29618800	0,21	0,06219948	0,00	Gaussian
v_a	0,20873930	V	0,00009857	-2,37	-0,00023361	0,00	Gaussian
δr_a	0	V	0,00350000	-2,37	-0,00829500	0,00	U-Quadratic
δG_a	0	V	0,00000003	-2,37	-0,00000007	0,00	Gaussian
δt_a	0	V	0,00086600	-2,37	-0,00205242	0,00	Uniform
δz	0	V	0,00141000	-2,37	-0,00334170	0,00	Uniform
k_{t-t}	619,782744	N/V	3,48578900	0,45	1,56860505	2,10	Gaussian
v_t	0,44823099	V	0,00012314	619,78	0,07632133	0,00	Gaussian
δr_t	0	V	0,00350000	619,78	2,16923000	4,01	U-Quadratic
δG_t	0	V	0,00001081	619,78	0,00669734	0,00	Gaussian
δt_t	0	V	0,00086600	619,78	0,53672948	0,25	Uniform
δz	0	V	0,00141000	619,78	0,87388980	0,65	Uniform
δa	0	N	10,2000000	1	10,2000000	88,74	Gaussian
δf	0	N	2,08000000	1	2,08000000	3,69	Gaussian
δv	0	N	0,27200000	1	0,27200000	0,06	Gaussian
F_t	278,7819	N	u_C =10,8279				Gaussian

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;
δa, δf, δv– cutting parameters uncertainty contributions,
a – dept of cut, f –feed rate, v – cutting speed;

Table 2 is representing the calculated uncertainty budget in the spirit of GUM [1].

More details about calculations of the standard uncertainties of the influence parameters can be found in [4]. Also there are more details about the overall analysis of the applied hardware and software architecture during the measurement process, as well as conclusions about the nature of the error sources and possible directions for improving the measurement process.

Further within the scope of this paper adaptive Monte Carlo procedure is applied. Software for the Monte Carlo simulations has been made in Matlab by using open source code as a base [6].

The comparison of the results between the GUF and MCS (MCS1) is given in the table 3 and figure 2a, and it can be stated that validation tool gave positive results for the selected parameters.

The linear mathematical model for propagation of the measurement uncertainty (1) consists of many parameters which are described with distributions given in table 2. Many factors influence on forming of the mathematical model output quantity: the number of input parameters, parameters' distribution, characteristics of the input parameters distributions, form of the mathematical model, value of the parameters, decision of the researcher which factors to include or to decompose, etc. Some of them depend on the physical reality and some of them on the research process. So, there is realistic possibility for not fulfilling the criteria for GUM application described in the introduction of this paper. Just one possible cause for outcome of unrealistic coverage interval in such mathematical model is let say different type of PDF of some influential parameter.

For example, we can change the type of PDF for the parameter δa from table 1 or model (1) from Gaussian to Uniform or U-Quadratic. The recalculated results are marked with MCS2 and MCS3 in the table 3 and represented in figures 2b and 2c respectively.

As in our assumption GUF calculation mechanism cannot represent the resulting changes in the form of the propagated output quantity for this example. Further this influences on the change of the probabilistically symmetric coverage interval and leads to negative validation with the applied MCS method for the selected criteria of the adaptive MCS procedure.

Additionally in table 3 (results for the endpoint differences of the probabilistically symmetric coverage interval) it is visible that even decreasing of the criteria of the MCS procedure for the numerical tolerance (to zero significant decimal places) cannot result in positive validation

These analyses allow us to propose that uncertainty evaluation of cutting force measurement should be followed by validation of the gained results by means of numerical method like MCS.

Tab. 3. Results of uncertainty calculations by different methods

Method	M	F_t	$u_C(F_t)$	Probabilistically symmetric 95% coverage interval	Δ_{low}	Δ_{high}	$\delta_{stab} = 0{,}05$ $\delta_{val} = 0{,}25$ GUF validated?
GUF		278,782	10,828	[257,559 - 300,005]			
MCS1	$1{,}22\cdot10^6$	278,797	10,828	[257,586 - 300,019]	0,027	0,014	YES
MCS2	$0{,}55\cdot10^6$	278,796	10,826	[259,782 - 297,818]	2,223	2,187	NO
MCS3	$0{,}38\cdot10^6$	278,796	10,806	[260,823 - 296,744]	3,264	3,261	NO

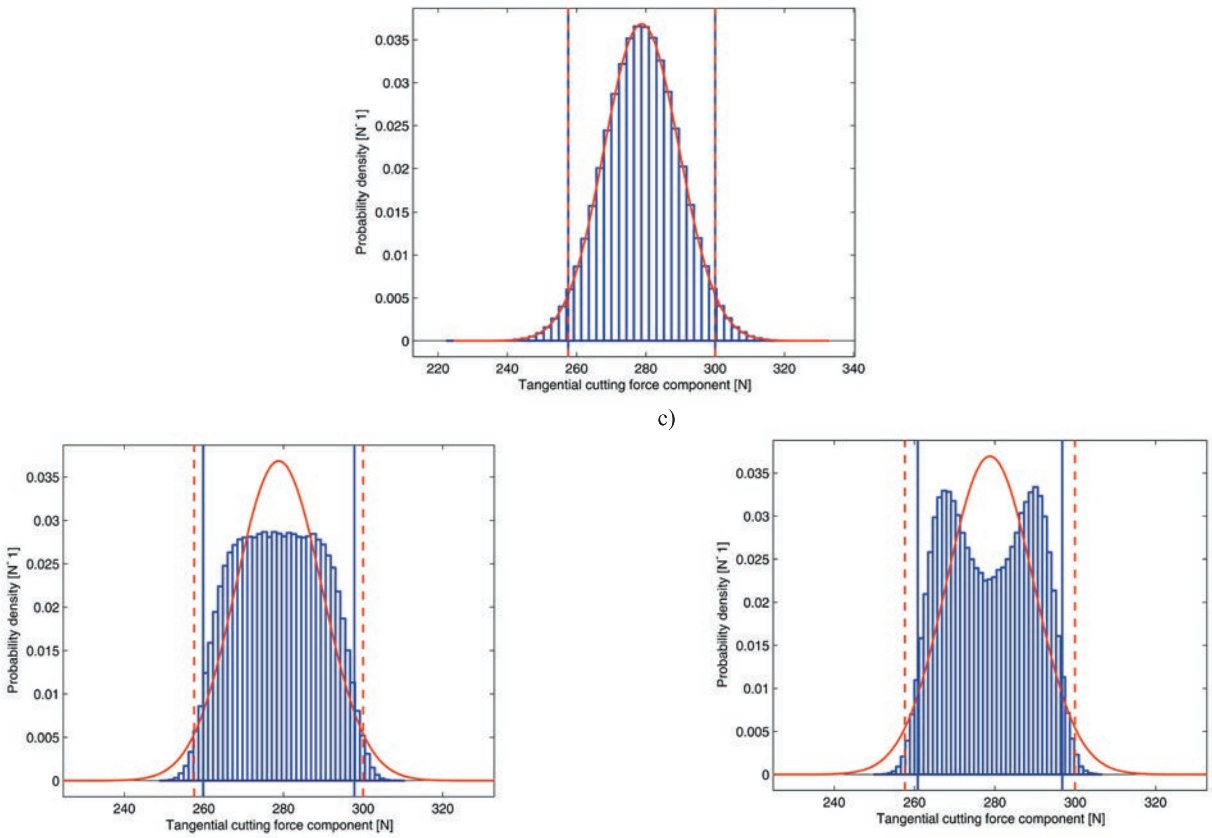
M – The numbers of Monte Carlo trials taken by the adaptive procedure

Δ_{low}, Δ_{high} – The endpoint differences of the probabilistically symmetric 95% coverage intervals

δ – Numerical tolerance (stab-stabilization criteria of the adaptive MCM procedure, val – validation criteria

a)

b)



------- shows the PDF resulting from the GUF

------- approximations constituting the discrete representation provided by MCS

Fig. 2. Probability distribution for the tangential cutting force component

Conclusions

In this study it is shown an example of experimental measurement of cutting force during machining with turning including associated parameter which describes the measurement uncertainty. Influences of the cutting process parameters are included like contributors on the measurement uncertainty. Measurement uncertainty is evaluated within the principles of GUM uncertainty framework as most widely accepted in the metrology community. The research showed that the complexity and the nature of the mathematical model used for propagation and evaluation of the measurement uncertainty can result in unreliable evaluation of the measurement uncertainty. Possible solution with example is proposed by application of the numerical method adaptive Monte Carlo simulations as validation tool for the applied GUF method. Such approach is proposed as adequate way for exploitation of the advantages of both methods or in contrary to avoid the disadvantages of both methods.

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