Outlook on measurement, uncertainty and mathematical representation of the physical phenomena that occur in machining processes

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Outlook on measurement, uncertainty and mathematical representation of the physical phenomena that occur in machining processes

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Abstract. In this article an outlook is given of our and other recent approaches of research and representation of the mathematical models of some physical phenomena that occur in the cutting process. The focus is on the mathematical power model reliability which can be evaluated by the uncertainty parameters based on all error contributors and presented along with the model. An algorithm is proposed for the recommended steps during experimental modelling of the cutting process and uncertainty estimation. The significance of certain errors sources from the measurement software, hardware and the cutting process itself is stressed.

1. Introduction

Following the recent analysis of modeling of metal machining process with the focus on the fundamental physical quantities (forces, temperature, stresses, etc.) we can find common views about the ongoing and future work in this field. Although there are achievements in the field of prediction of forces, temperatures, stresses, strains in 2D and 3D by mechanistic, analytical, numerical and FEM models, it is expected that there will be a significant contribution for reduction of uncertainty and developing of experimental techniques for 2D and 3D measurement. It is suggested that the predictive models should take into account the empirical uncertainty, but we can also agree with the statements about the lack of documentation on measurement uncertainties [1-5].

Having a representation of the measurement uncertainty, in general, is essential for identification and reduction of error sources. Furthermore, this is also a solution for explaining the discrepancies between the models of different research methods. Models with accompanied lower uncertainty values will be more valuable when used in the manufacturing process and in the product quality design. Consequently, they will be more reliable. The size of the accompanied uncertainty value also determines if the fitted mathematical models can be used only for general guidance in the selection of the cutting parameters, for increasing the quality of the production, or even for advanced design of the machined surface layer. Following are the comparison of some results of uncertainty budget analysis, identification of the most common error sources and proposed steps in the empirical mathematical modeling with an accompanied uncertainty parameter.

2. Measurement uncertainties of the physical quantity

If we want to make a general statement about empirical modeling in the cutting process, we can say that although there is a lack of published data in this field, there is a common perception that measurement uncertainty estimation is recommended and expected in the ongoing and future researches.

In this paper we want to give one short outlook based on our research data and applied investigation methodology about: the main contributors of the measurement uncertainty, the ways of the measurement uncertainty representation, the recommendations for reducing the measurement uncertainty, and the recommendation for research steps in empirical modeling.

2.1. Measurement uncertainty contributors

During our investigation of some physical quantities by using own developed experimental stand and computer aided measurement, we have tabularized the uncertainty budgets. For instance, if we make a comparison between different investigated quantities or between different researchers as given in Table 1, we can observe that:

- Measurement uncertainty budgets in most of the cases is expected to be dissimilar because even a small change in the experimental setup or applied methodology will lead to large uncertainties;
- It is essential to include the process related sources, as they can be the main contributors. Including only the measuring equipment uncertainty for certain will lead to underestimating the overall combined measurement uncertainty;
- The cutting process parameters, the feed rate and the depth of cut are large contributors to the measurement uncertainty. It is very important for ongoing and future researches to report the different, and hopefully more efficient approaches to lower the errors from measuring of these quantities;
- The calibration procedure and methodology is one of the most significant uncertainty contributor;
- The other uncertainty sources should be carefully removed from consideration if they do not significantly contribute to the uncertainty budget. This will help to focus the research on lowering the errors from the significant contributors, and it will make the research cost-effective.

This implies that very often the investment in research measurement equipment in order to lower the errors, is not reasonable. The trend of raising the criteria of using modern research experimental equipment in order to have reliable measurement data by research centers or scientific publishing agencies is not justified as well.

Table 1. Relative contribution in the combined standard uncertainty during single quantity measurement.

Contributors	Researched physical quantity		
	Cutting force		Average cutting temperature
	Axinte et al. [6]	Trajchevski et al. [7]	Trajchevski [8]
Calibration procedure	60.9%	6.1%	72.6%
Feed rate	36.6%	3.7%	14.2%
Depth of cut	1.9%	88.7%	8.7%
Other	0.6%	1.5%	4.5%

2.2. Measurement uncertainty representation

Determining the error during the experimental investigations and statistical regression adequacy tests is not sufficiently questioned within the published papers during empirical modeling. Therefore, this might mean that many published results have significant limitation of their reliable interpretation and further use. Of course, the question that arises from this issue is what the right approach is.

Herein we address to the example of fitting power mathematical model. The generating power empirical models, as the model exponents directly represent the physical meaning or the influence rate (the trend) of the parameter, is a very convenient way of empirical modeling. The inconvenient part refers to modeling them by using methods like Design of Experiments (DOE), where the error is handled within the linearized model form in logarithmic values. The approaches to enhance the gained model with measurement uncertainty parameter are following.

2.2.1. Single measurement uncertainty only

A recent common and essential step is to determine the combined standard uncertainty during a single quantity measurement and to form the uncertainty budget as the examples given in [6], [7]. Furthermore, Axinte [6] proposes a linear model that predicts a single cutting force expanded uncertainty *UF*, for a defined range of cutting parameters equation (1).

$$UF = H + K \cdot a_p + L \cdot f \tag{1}$$

where *H*, *K* and *L* are the model coefficients and a_p and f are the cutting parameters. Although this model can be convenient for saving time during a single force uncertainty estimation in every point of the experimental plan, it is a question that maybe itself generates equation fitting error. Additionally, the final result of the experimental investigation, the modelled cutting force vs. the cutting parameters, is not accompanied by any parameters related to the previously calculated single measurement uncertainty. Not knowing the rate of uncertainty of the final mathematical model brings us limited knowledge of whether our model is reliable and what its potential use is.

2.2.2. Final model exponents (coefficients) measurement uncertainty

A different approach that we proposed in our published papers is to use the measurement uncertainty of a single experimental plan measured point in order to be propagated by the DOE matrix equation and to result with the final power model exponent (coefficient) uncertainties. The final model with accompanied uncertainty parameters is showed by the equation (2).

$$T_C = \left(C \pm U_C\right) \cdot v^{p_1 \pm Up_1} \cdot f^{p_2 \pm Up_2} \cdot a^{p_3 \pm Up_3} \cdot r_\varepsilon^{p_4 \pm Up_4} \tag{2}$$

where T_C is the modelled physical quantity, *C* and p_i are the model exponents (coefficients), v, f, a, r_ε are the cutting process parameters and U_C, Up_i are the expanded model exponent uncertainties. As the propagated exponent uncertainty depends on the propagation model (based on DOE) matrix, different experimental plans or replicas will give different exponent uncertainty. It is encouraging to have more similar research approaches in this field in order to recommend the best one.

2.3. Measurement uncertainty size

It is expected that under the best calibration condition and well controlled measurements, the size of the measurement uncertainty would be within ±10%, otherwise it will be considered as a methodology or data error. From our experimental research result we can report values as presented in Table 2, showed along with the results of Axinte for comparison. In the next section, we can give some directions in order to lower the size of a single measurement uncertainty, and we believe that more published results in this field can lead to accepting measurement practices and methods that will lower expected measurement uncertainty reaching a half of what is now considered acceptable. The other important observation is that depending on the propagation model, in our example of a DOE matrix, the final power exponent uncertainty can be within a much wider domain, as presented in the last row

in Table 2. And this is maybe the most important information when representing the final empirical model, as it shows how reliable the exponent value is. If this value is very high, we cannot consider the trend described by the exponent as sufficiently reliable.

Table 2. Relative expanded measurement uncertainty.

	Researched physical quantity		
	Cutting force		Average cutting temperature
	Axinte et al. [6]	Trajchevski et al. [7]	Trajchevski [8]
Relative expanded measurement uncertainty of a single measurement	3.2%	7.7%	1.5%
Mathematical power model exponent (coefficient) relative expanded uncertainty			5-50%

2.4. Recommendations for good measuring practices in order to obtain proper and lower measurement uncertainty

The researcher's approach must be towards, not only lowering the uncertainty, but also obtaining the proper value. For example, during the determination of a single measurement uncertainty as part of the DOE experimental plan point, the deviations of the measured depth of cut or feed rate should be calculated upon the assumed mean, which is the experimental plan parameter value. Otherwise, uncertainty will be underestimated. The most useful recommendations for lowering the uncertainty should definitely be related to the biggest contributors showed in Table 1. However, in this paper we can give only a general and limited number of recommendations, whereas for detailed results the published results and applied methodologies from our and other works should be considered.

2.4.1. Feed rate contribution

Our approach to determine the feed rate uncertainty was by using the machined surface roughness parameter which is depicturing the feed rate, as opposed to Axinte whose approach refers to using distance/time method from the CNC lathe monitoring equipment. Our observations are focused on the fact that every change in the cutting parameters has a different impact on the feed rate deviation. This results in a different uncertainty contribution in different experimental plan measurements and should be approached separately.

2.4.2. Depth of cut contribution

If the tool wear parameter is not in the research scope, then using only new tools and a short cutting time is a way to lower the depth of cut uncertainty. We can recommend using metrology laboratory methods for measurement of the workpiece diameter and efforts to exclude errors from the machine-tool-workpiece stiffness during the cutting process.

2.4.3. Calibration procedure contribution

As this looks like the main contributor in the uncertainty budget, a more accurate methodology should be practiced. Our successful approach to lower the calibration of the dynamometer while investigating the cutting forces can serve as an example. We have concluded that the uncertainty of a deadweight load (accredited laboratory measured) is significantly lower in comparison to the universal testing machine. We can recommend using a state-of-the-art high linearity amplifiers in order to achieve lower uncertainty from the calibration lines. Additionally, in this part we can recommend using galvanic separation between the signals which result from the process and the amplifier circuit. As an example we prefer to use optically coupled signal amplifiers.

3. Summary of the recommended procedure

For estimation of the uncertainty of the final result of an empirical investigation of research quantity, we can propose but not limit the approach to the steps showed on Figure 1. It can be stated that in order to have a reliable mathematical model as a result of the experimental research, it is necessary to have a multidisciplinary approach starting with the development of methods of research and modeling to developing of the experimental equipment to fit the scientific process. Significant steps are identification and determination of error sources from the measurement equipment and from the cutting process. And even more significant is how these errors are combined and propagated in the resulting measurement uncertainty. As the combined measurement uncertainty will be based on standard measurement uncertainties with different distributions it is proposed a step of verification with numerical methods. The crucial final steps are proposed to be suitable representation of the uncertainty in order to have physical meaning and the graphical representation can help in the estimation of the reliability of the final results.

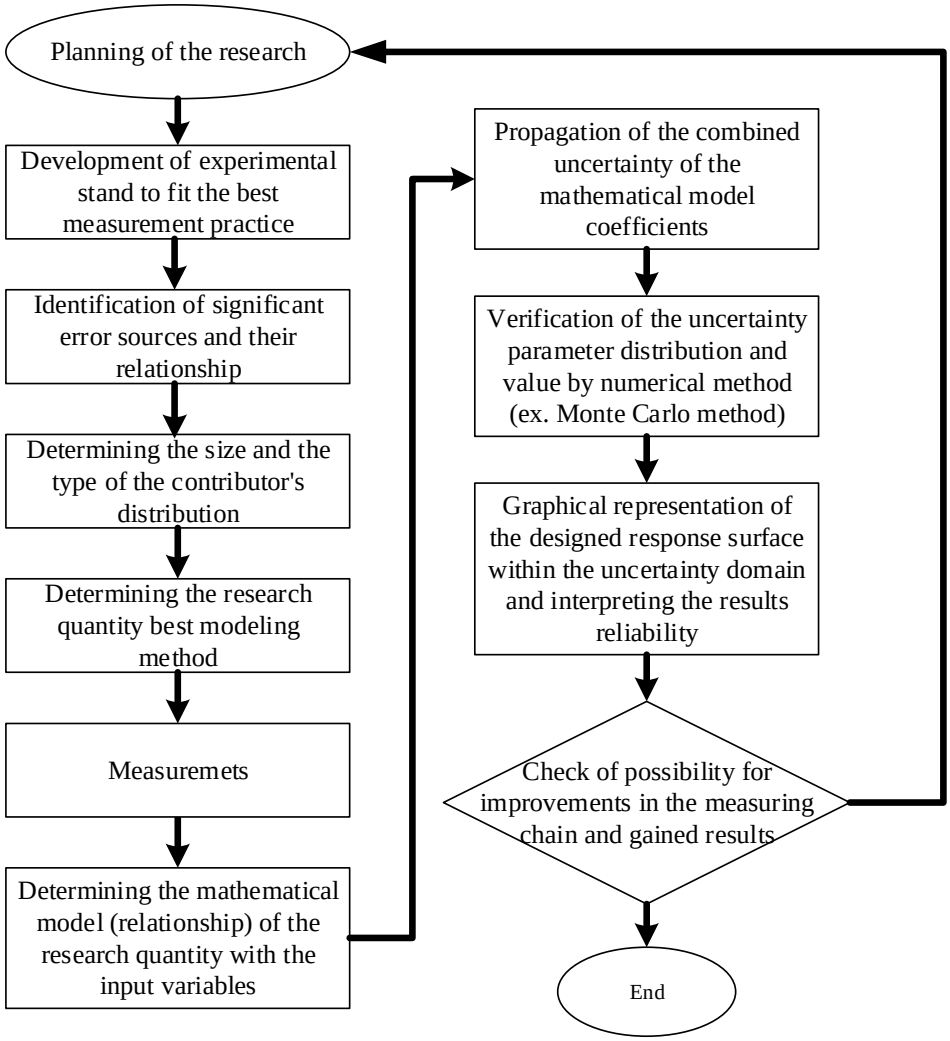

Figure 1. Recommended steps during experimental modeling of the cutting process with uncertainty estimation.

The proposed steps are the summary of our many years of research in the field of improving the quality of experimental scientific research in machining processes, and it is backed up by our already published and papers in the process of publishing.

4. Conclusions

Advantage should be given to good measurement practice and methodology, rather than developing new time-consuming approaches or investing in equipment. It is proposed that measurement uncertainty determination should be regular practice during empirical modeling. Also it is proposed that the uncertainty parameter should be represented in suitable form within the mathematical model representation in order to show the reliability of the model. The proposed steps of experimental modeling process can be generalized in the field of mechanics and even in other fields. Such a comprehensive approach should lower the discrepancies in the research results obtained by different institutions.

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