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Evaluation of measures for thermo-sensitive design and operating of machine tool structures

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Abstract

The variance-based sensitivity analysis can be used as a statistical procedure to evaluate different individual measures to influence the thermal behaviour of machine tools. It provides specific ratios for parameters affecting the variance of the output parameters that are not comparable in any other way. This method is implemented by means of large samples used in a simulation model which reduces computing time and is oriented towards physical objects. Furthermore, conditional and total variances are estimated. The article describes the principles of modelling with discrete elements to integrate all variants into one simulation model, the definition of input and output parameters and sample generation considering the parameter-specific distribution functions and parameter dependences. To evaluate the applied measures, temperatures, temperature differences, heat flow and time required until achieving thermal equilibrium are examined as such, or in relation to the deployed energy. The implementation is demonstrated by means of two examples. One refers to the design, and the other one deals with the operation phase of existing machine tools.

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Keywords: Machine tool; sensitivity analysis; thermal measures; design phase; adaptive cooling

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1. Measures to influence the thermal behaviour

In modern machine tools, the thermal drift phenomenon often causes up to 70% of geometric workpiece errors [1]. The implementation of measures to influence the thermal behaviour is mostly experience-based or requires extensive preliminary investigations. Currently developers are obliged to choose between countless thermo-mechanical methods without being able to state precisely which one has the best effects for the specific case of application. In industrial applications an unreflective approach is often pursued under the motto “the more, the better“. Thus, in some cases machine beds are completely suffused to achieve the nominal temperature, machines remain in position-controlled states even when machining is interrupted or the quantities of cooling lubricant used during machining are significantly and disproportionately increased. The employment of these measures frequently counteracts the original goal of energy efficiency.

Nomenclature

c_p	specific heat capacity
m	mass
t	time
C	heat capacity
L	thermal conductivity
P_{th}	thermal power
$\dot{Q}$	heat flow
R_{th}	thermal resistance
S_i, S_{Ti}	sensitivity measures: main effect, total effect
V	volume
X_i, Y	input parameter, output parameter
ρ	density
ϑ	temperature

The different measures for influencing the thermal behaviour are illustrated along the thermo-elastic functional chain [2]. A categorized overview is given in Table 1.

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Table 1. Measures for influencing the thermal behaviour, subdivided regarding the point of intervention within the thermo-elastic functional chain.

Influence on:	Passive measures	Active measures
Heat flow	Reduction of emerging heat (technology) Reduction of emerging heat (energy efficiency) Insulation of heat sources	Environment of the machine Heat sources inside the machine
Temperature field	Thermal conductivity Heat transfer Heat storage	Internal cooling by fluids External cooling Tempering Heating
Deformation field	Design Thermal expansion (material)	Correction measures (Control) Deformation compensation

Modifications at heat sources come closest to the cause of thermal errors. These modifications allow for adaptation and specific reduction of the heat flows that are dissipated into the machine structure. The aim of these measures is to avoid structural temperature changes. Moreover, it is possible to avoid large spatial as well as large temporal temperature gradients by correcting the developed temperature field. These approaches pursue a reduction of structural temperature changes. The third possibility lies in reducing the thermally induced formation of the deformation field or in limiting its effects. Thus, these measures directly target the effects within the thermo-elastic functional chain rather than the causes.

Furthermore, the measures are subdivided into passive and active measures, as suggested in [3]. Passive measures are implemented in the design phase of a product. They do not require any direct input of external energy. They include all structural and design approaches such as thermally symmetric layout, insulation or enclosure of heat sources, appropriate material selection and avoiding of large installation lengths which are highly susceptible to temperature increases. In comparison, active measures include interventions into the heat balance by an input of external energy on the one hand; on the other hand they comprise control-integrated adjustments of feed drives or additional control axes. They are carried out by using various measuring sensors to determine the actual thermal or the thermo-elastic state. They also require additional input of information and energy.

Regarding the amount of measures for influencing thermal behaviour, it is obvious that a fast and reliable comparative statement is not possible concerning their particular effectiveness with respect to desired temperature behaviour. To evaluate the efficiency of thermal measures there are just rudimental possibilities like the method of thermal modal analysis [4].

2. Sensitivity analysis

The variance-based sensitivity analysis can be used as a statistical procedure to evaluate different individual measures for influencing the thermal behaviour of machine tools. It provides specific ratios for parameters affecting the variance of the output parameters that are not comparable in any other way [5]. The basic idea behind this procedure is to separate the total variance of the output parameter and assign it to the several influencing parameters, see Fig. 1.

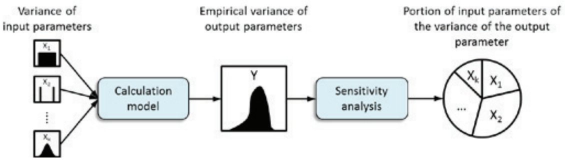

Fig. 1. Approach for variance-based sensitivity analysis (in compliance with [6]).

In the variance-based sensitivity analysis the so-called sensitivity measures S_i are determined for each factor X_i using variances and conditional expectations [5]. They are measures of the immediate impact of the i-th parameter on the variance of one output parameter Y (for convenience it is described only for one output parameter here; it is possible to extend it to further variables, which is described subsequently):

$$S_i = \frac{Var\left[E\left(Y \middle| X_i\right)\right]}{Var\left[Y\right]} \tag{1}$$

This sensitivity measure indicates the first order effect (without consideration of interactions) of the i-th factor. This quantitative sensitivity measure is a normalized index that always varies between zero and 1. The greater the value, the more influencing the effect. A sum of the first order sensitivity coefficients of all considered input variables considerably smaller than 1 is an indicator for additional effects of interaction within the model. In non-linear systems these effects of interaction can be significant. They are incorporated into the calculation of total effects:

$$S_{Ti} = \frac{E\left[Var\left(Y \middle| X_{-i}\right)\right]}{Var\left[Y\right]} \tag{2}$$

This total effect index S_{Ti} measures the total effect of the i-th factor to the variance of the output variable Y while considering interactions. For this reason it is not possible to draw the conclusion that a factor with a small first order effect has only little influence on the total variance of a corresponding output value. Only if the total effect of the factor is also small, such a statement holds true.

The solution is provided according to the procedure shown in [7] using a statistical estimation of vast samples based on a Monte-Carlo simulation. Based on two matrices $\mathbb{A}_{\mathrm{n}\times\mathrm{k}}$ and $\mathbb{B}_{\mathrm{n}\times\mathrm{k}}$ which represent an n-dimensional sample of k different input variables and a third matrix $\mathbb{A}_{\mathbb{B}}^{(\mathrm{i})}$, which combines the first two matrices in a defined way, the corresponding functional values are calculated and stored in the matrices $\mathrm{f}_{\mathbb{A}}$, $\mathrm{f}_{\mathbb{B}}$ and $\mathrm{f}_{\mathbb{A}_{\mathbb{B}}^{(\mathrm{i})}}$. The conditional and the total variance of the output parameters required for Eq. (1) and (2) is determined by means of adequate estimations. Estimations are applied