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VIRTUAL PROTOTYPING OF MACHINE TOOLS

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The monograph aims to familiarize the professional public with the results of the research on increasing the working accuracy of machine tools at the stage of their virtual prototyping using numerical simulations. The identification of the effects of the machining process itself as well as the impact of machine design features will allow it to predict and subsequently optimize its construction in terms of its working accuracy. The publication draws on the results of the authors' own research activities within the VEGA grant project No. 1/0124/15 Research and development of advanced methods for virtual prototyping of manufacturing machines and No. 039TUKE-4/2016 The creating of virtual laboratories based on web technologies to support the educational process in the field of Manufacturing Technology

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CONTENT

PREFACE

We have prepared the presented scientific monograph in order to familiarize the public with some research results on the possible enhancement of working accuracy of machine tools at the stage of their virtual prototyping. The identification of the effects of the machining process itself as well as the impact of machine design features will allow it to predict and subsequently optimize its construction in terms of its working accuracy. The practical importance of virtual machining is primarily the reduction of financial costs and acceleration of machine design without the need to produce a physical prototype. Using simulation models, it is possible to repeatedly analyze the weak spots of the machine design, to determine the effects of each machine component on its properties and to optimize them, but also to take account of ergonomic and other requirements. In the publication of the mentioned virtual machining methodology and the corresponding simulation models, two basic types of machine tools were developed - for machines for machining rotary parts (turning machines with horizontal axis of spindle) and machines, respectively machining centres for machining non-rotating workpieces of small to medium dimensions.

The publication draws on the results of the authors' own research activities within the VEGA grant project No. 1/0124/15 Research and development of advanced methods for virtual prototyping of manufacturing machines and previous grant research projects whose partial results have been published in the works listed in the references. The elaborated and verified methodises of virtual machining and simulation of the machining process are developed by the Department of Manufacturing Machines and Equipment and can be used in industrial practice for existing and / potential manufacturers of machine tools.

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Authors

Devoted to our dear wives, children and grandchildren

USED DESIGNATIONS

A		marking the examined point of model body
A_k		marking the examined point of model body in the position at the beginning of machining
A_p		marking the examined point of model body after displacement
A_φ		marking the examined point of model body after rotation around the axis X_i
A_υ		marking the examined point of model body after rotation around the axis Y_i
A_ψ		marking the examined point of model body after rotation around the axis Z_i
a	(mm)	dimension from machine design
a_1	(mm)	dimension from machine design
a_p	(mm)	cutting depth
B	(mm)	dimension from machine design
B_{omax}	(mm)	maximum workpiece width
B_{omin}	(mm)	minimum workpiece width
B_4	(mm)	dimension from machine design
B_5	(mm)	dimension from machine design
b	(mm)	dimension from machine design
b_f	(mm)	milling width
c	(mm)	dimension from machine design
c_1	(mm)	dimension from machine design
c_2	(mm)	dimension from machine design
c_3	(mm)	dimension from machine design
D_L	(mm)	diameter of the spindle between the bearings
D_p	(mm)	workpiece diameter before machining
d	(mm)	dimension from machine design
d_f	(mm)	diameter of the milling cutter
d_{fmax}	(mm)	maximum diameter of the milling cutter
e	(mm)	dimension from machine design
e	(mm)	radial throwing of the front end of the spindle
e_1	(mm)	dimension from machine design
e_2	(mm)	dimension from machine design
e_3	(mm)	dimension from machine design
e_a	(mm)	axial throwing of the front end of the spindle
e_p	(mm)	radial throwing of the front bearing of the spindle
e_z	(mm)	radial throwing of the rear bearing of the spindle
F_c	(N)	tangential component of the cutting force
F_f	(N)	axial component of the cutting force
F_p	(N)	radial component of the cutting force
F_X	(N)	cutting force component in the X axis direction
F_Y	(N)	cutting force component in the Y axis direction
F_Z	(N)	cutting force component in the Z axis direction
f	(mm)	dimension from machine design
f_X	(mm)	feed rate in the X axis direction
f_Y	(mm)	feed rate in the Y axis direction

f_Z	(mm)	feed rate in the Z axis direction
f_1	(mm)	dimension from machine design
f_2	(mm)	dimension from machine design
f_3	(mm)	dimension from machine design
f_4	(mm)	dimension from machine design
f_{10}	(mm)	dimension from machine design
f_{11}	(mm)	dimension from machine design
f_{12}	(mm)	dimension from machine design
g	(mm)	dimension from machine design
g_1	(mm)	dimension from machine design
g_2	(mm)	dimension from machine design
g_3	(mm)	dimension from machine design
H_o	(mm)	workpiece height
H_{omax}	(mm)	maximum workpiece height
H_{omin}	(mm)	minimum workpiece height
H	(mm)	dimension from machine design
H_3	(mm)	dimension from machine design
H_4	(mm)	dimension from machine design
H_5	(mm)	dimension from machine design
h	(mm)	dimension from machine design
h_f	(mm)	milling depth
h_1	(mm)	dimension from machine design
h_2	(mm)	dimension from machine design
h_3	(mm)	dimension from machine design
h_4	(mm)	dimension from machine design
h_5	(mm)	dimension from machine design
k	(mm)	dimension from machine design
k_1	(mm)	dimension from machine design
k_2	(mm)	dimension from machine design
L_{eopt}	(mm)	optimal distance between the spindle bearings
L_i	(mm)	distance between the spindle bearings
L_o	(mm)	workpiece length
L_{omax}	(mm)	maximum workpiece length
L_{omin}	(mm)	minimum workpiece length
L_2	(mm)	dimension from machine design
L_3	(mm)	dimension from machine design
L_4	(mm)	dimension from machine design
L_5	(mm)	dimension from machine design
l	(mm)	dimension from machine design
m	(mm)	dimension from machine design
n	(mm)	dimension from machine design
n_v	(min^{-1})	spindle speed
0_i		origin of the model body T_i coordinate system
0_{in}		origin of the model body T_i coordinate system in position after rotation
0_{ip}		origin of the model body T_i coordinate system in position after displacement
0_n		origin of the tool coordinate system
0_0		origin of the workpiece coordinate system

p	(mm)	dimension from machine design
R_p	(mm)	radius of the semi-finished product
R_{max}	(mm)	maximum really machined radius
R_{min}	(mm)	minimum really machined radius
r_ε	(mm)	the tip radius of the cutting wedge
S_i		coordinate system of T_i model body
T_i		designation of the model body (the index determines its order)
t	(s)	time - general designation
$t_{(\mathrm{min})}$	(min)	time in minutes
$t_{(\mathrm{s})}$	(s)	time in seconds
$u_i(t)$	(mm)	instantaneous path of the model body T_i in the direction of the X_i axis
v_c	($\mathrm{m \cdot min^{-1}}$)	cutting speed
v_{fX}	($\mathrm{mm \cdot min^{-1}}$)	feed speed in the direction of the X_i axis
v_{fY}	($\mathrm{mm \cdot min^{-1}}$)	feed speed in the direction of the Y_i axis
v_{fZ}	($\mathrm{mm \cdot min^{-1}}$)	feed speed in the direction of the Z_i axis
$v_i(t)$	(mm)	instantaneous path of the model body T_i in the direction of the Y_i axis
$w_i(t)$	(mm)	instantaneous path of the model body T_i in the direction of the Z_i axis
X		general designation of the axis of the coordinate system of the machine tool
X_i		designation of the axis of the coordinate system of the model body T_i
$X_{in\upsilon}$		designation the X_i axis after rotation of the model body T_i around the Y_i axis
$X_{in\psi}$		designation the X_i axis after rotation of the model body T_i around the Z_i axis
X_{ip}		designation the X_i axis after displacement of the model body T_i
x_i	(mm)	coordinate on the X_i axis
x_{ik}	(mm)	x-coordinate of point A_k in the coordinate system of the model body T_i
$x_{0,i+1}$	(mm)	x-coordinate of the origin of the T_{i+1} model body coordinate system in the coordinate system of the T_i model body at the beginning of machining
Y		general designation of the axis of the coordinate system of the machine tool
Y_i		designation of the axis of the coordinate system of the model body T_i
$Y_{in\varphi}$		designation the Y_i axis after rotation of the model body T_i around the X_i axis
$Y_{in\psi}$		designation the Y_i axis after rotation of the model body T_i around the Z_i axis
Y_{ip}		designation the Y_i axis after displacement of the model body T_i
y_i	(mm)	coordinate on the Y_i axis
y_{ik}	(mm)	y-coordinate of point A_k in the coordinate system of the model body T_i
$y_{0,i+1}$	(mm)	y-coordinate of the origin of the T_{i+1} model body coordinate system in the coordinate system of the T_i model body at the

		beginning of machining
Z		general designation of the axis of the coordinate system of the machine tool
Z_i		designation of the axis of the coordinate system of the model body T_i
$Z_{in\varphi}$		designation the Z_i axis after rotation of the model body T_i around the X_i axis
$Z_{in\upsilon}$		designation the Z_i axis after rotation of the model body T_i around the Y_i axis
Z_{ip}		designation the Z_i axis after displacement of the model body T_i
z_f		number of teeth of the cutter
z_i	(mm)	coordinate on the Z_i axis
z_{ik}	(mm)	z-coordinate of point A_k in the coordinate system of the model body T_i
$z_{0,i+1}$	(mm)	z-coordinate of the origin of the T_{i+1} model body coordinate system in the coordinate system of the T_i model body at the beginning of machining
Θ	(mm)	roundness of the cross section
$\alpha_i(t)$	(rad)	instantaneous angle of rotation of the model body T_i around the X_i axis
α_0	(°)	tool back angle in the orthogonal plane
$\beta_i(t)$	(rad)	instantaneous angle of rotation of the model body T_i around the Y_i axis
$\gamma_i(t)$	(rad)	instantaneous angle of rotation of the model body T_i around the Z_i axis
γ_0	(°)	tool forehead angle in the orthogonal plane
κ_r	(°)	angle of the adjusting of the main cutting edge
λ_s	(°)	angle of inclination of the cutting edge
Δx_i	(mm)	deviation of the position of the point A in the X_i direction after the T_i model body rotates about the Y_i and Z_i axes
$\Delta x_{\upsilon i}$	(mm)	deviation of the position of the point A in the X_i direction after the T_i model body rotation around the Y_i axis
$\Delta x_{\psi i}$	(mm)	deviation of the position of the point A in the X_i direction after the T_i model body rotation around the Z_i axis
Δy_i	(mm)	deviation of the position of the point A in the Y_i direction after the T_i model body rotates about the Z_i and Z_i axes
$\Delta y_{\varphi i}$	(mm)	deviation of the position of the point A in the Y_i direction after the T_i model body rotation around the X_i axis
$\Delta y_{\psi i}$	(mm)	deviation of the position of the point A in the Y_i direction after the T_i model body rotation around the Z_i axis
Δz_i	(mm)	deviation of the position of the point A in the Z_i direction after the T_i model body rotates about the X_i and Y_i axes
$\Delta z_{\varphi i}$	(mm)	deviation of the position of the point A in the Z_i direction after the T_i model body rotation around the X_i axis
$\Delta z_{\upsilon i}$	(mm)	deviation of the position of the point A in the Z_i direction after the T_i model body rotation around the Y_i axis
δ_{xi}	(mm)	displacement of the origin of the coordinate system of the model body T_i in the X_i axis direction
δ_{yi}	(mm)	displacement of the origin of the coordinate system of the

		model body T_i in the Y_i axis direction
δ_{zi}	(mm)	displacement of the origin of the coordinate system of the model body T_i in the Z_i axis direction
$\varphi_i(t)$	(rad)	angular inaccuracy - rotation of the model body T_i around the X_i axis
φ_0	(rad)	angular inaccuracy - rotation of the workpiece around the X_0 axis
$\upsilon_i(t)$	(rad)	angular inaccuracy - rotation of the model body T_i around the Y_i axis
υ_0	(rad)	angular inaccuracy - rotation of the workpiece around the Y_0 axis
$\psi_i(t)$	(rad)	angular inaccuracy - rotation of the model body T_i around the Z_i axis
ψ_0	(rad)	angular inaccuracy - rotation of the workpiece around the Z_0 axis
ω_v	(rad·s^{-1})	angular spindle speed

MATRICES AND VECTORS DESIGNATION

$[\mathbf{E}]$	identity matrix
$\{\mathbf{K}_{i+1,i}\}$	starting position vector of the model body T_{i+1} coordinate system in the T_i model body coordinate system
$\{\mathbf{0}\}$	null vector
$[\mathbf{R}_{i+1,i}(t)]$	the rotational motion transformation matrix of the model body T_{i+1} relative to the T_i model body
$[{}^{X}\mathbf{R}_{i+1,i}(t)]$	the rotational motion transformation matrix of the model body T_{i+1} relative to the T_i model body around the axis X_i in any sense
$[{}^{Y}\mathbf{R}_{i+1,i}(t)]$	the rotational motion transformation matrix of the model body T_{i+1} relative to the T_i model body around the axis Y_i in any sense
$[{}^{Z}\mathbf{R}_{i+1,i}(t)]$	the rotational motion transformation matrix of the model body T_{i+1} relative to the T_i model body around the axis Z_i in any sense
$[{}^{Z+}\mathbf{R}_{i+1,i}(t)]$	the rotational motion transformation matrix of the model body T_{i+1} relative to the T_i model body around the axis Z_i in a positive sense
$[{}^{Z-}\mathbf{R}_{i+1,i}(t)]$	the rotational motion transformation matrix of the model body T_{i+1} relative to the T_i model body around the axis Z_i in a negative sense
$\{\mathbf{r}_i(t)\}$	the position vector of any point of the model body T_{i+1} in the coordinate system of the model body T_i
$\{\mathbf{r}_{i+1}(t)\}$	the position vector of any point of the model body T_{i+1} in his coordinate system
$\{\mathbf{r}_{i\delta}\}$	position vector of any point on the model body T_i after changing its position due to linear positional inaccuracies
$\{{}^{k}\mathbf{r}_i\}$	the position vector of any point of the model body T_{i+1} in the

	coordinate system of the model body T_i in the position at the beginning of machining
$\{\mathbf{r}_n\}$	tool contact point position vector in the tool carrier coordinate system (model body T_n)
$\{\mathbf{r}_0(t)\}$	tool contact point position vector in the workpiece coordinate system (model body T_0)
$\{\mathbf{T}_{i+1,i}(t)\}$	the linear motion transformation vector of the model body T_{i+1} relative to the T_i model body
$\{{}^X\mathbf{T}_{i+1,i}(t)\}$	the linear motion transformation vector of the model body T_{i+1} relative to the T_i model body in the X_i axis direction
$\{{}^Y\mathbf{T}_{i+1,i}(t)\}$	the linear motion transformation vector of the model body T_{i+1} relative to the T_i model body in the Y_i axis direction
$\{{}^Z\mathbf{T}_{i+1,i}(t)\}$	the linear motion transformation vector of the model body T_{i+1} relative to the T_i model body in the Z_i axis direction
$\{\Delta(t)\}$	vector of resulting inaccuracy of machining
$\{\Delta_i(t)\}$	the resulting position inaccuracy vector of the T_i model body
$\{\Delta_{\delta i}\}$	the vector component of the resulting position inaccuracy of the model body T_i taking into account the influence of the linear inaccuracies of its position
$\{\Delta_{\varepsilon i}\}$	the vector component of the resulting position inaccuracy of the model body T_i taking into account the influence of the angular inaccuracies of its position
$\{\delta_i(t)\}$	vector of the linear position inaccuracies of the model body T_i
$\{\delta_0(t)\}$	vector of the linear position inaccuracies of the workpiece
$\{\varepsilon_i(t)\}$	the matrix of angular inaccuracies of the position of the model body T_i
$\{\varepsilon_0(t)\}$	the matrix of angular inaccuracies of the position of the workpiece

INTRODUCTION

In general, it can be stated that it is highly unlikely for a field of human activity to exist completely unrelated to production technology, where the dominant position is apparently occupied by machine tools. Machine tools are involved (whether directly or indirectly) in the production of virtually any product, so their improvement, streamlining, increasing the quality of production, and the ability to respond flexibly to customer requirements are essential.

Machine tool manufacturers are constantly working to reduce the time and cost needed to launch a new machine tool on the market. Considerable time savings can be achieved at the development stage of the new machine by gradually eliminating the need to manufacture its prototype, and by verifying the properties of newly engineered machine through simulation models. This principle of the so-called virtual prototyping is already commonly used, for example, in the aviation and automotive industry and is supported by the existence of powerful hardware, but equally so by perfect software products.

Computational design support for machine tools through analyses utilizing the finite element method is now a common part of their development process. Standard structure-related calculations are those of their static, dynamic (modal analysis) and thermal properties. However, requirements for the level of sophistication of machine tool structures are constantly on the rise. The market demands solutions that reduce production times and make the production process more efficient as a whole, while increasing the machining precision of workpieces. High-Speed Cutting applications are highly dynamic processes to which the concept and design of machines must be tailored accordingly.

Standard computational simulation methods no longer suffice to successfully meet all of the requirements for the construction of advanced-level machines. Behaviour simulation of the mechanical part of the machine design must be considered, taking into account the processes directly related to the operation of the machine and significantly affecting its properties and achievable machining precision. At the EMO - global trade fairs for machine tools, a number of computational simulation solutions have been recorded over the years in all of the above-listed areas.

The production and testing of the physical prototype of any technical object is both time consuming and costly. Therefore, it is necessary to intensify the research, development, verification and practical implementation of various rapid prototyping methods. One of the possibilities is virtual prototyping of machine tools based on the principle of virtual machining, which tests the properties of the proposed technical work on its mathematical models.

The presented paper demonstrates the possibilities of practical applications of virtual machining with the machine tools prototyped virtually. The entire topic is divided into seven chapters.

The first chapter explains the basic theoretical principles and the mathematical relationships necessary for creation of mathematical models for the explored problems - modelling of tool trajectories during machining, modelling of the influence of inaccuracies in the set: machine – tool – workpiece, on working accuracy of the machine tool.

The second chapter explains the principles of computational modelling of explored problems.

The chapters three to seven focus on presentation of selected research results on machine tools from the field of virtual machining.

The problem of machine tool precision and its mathematical modelling in this paper is narrowed to cover only the most extensive group of machine tools that make up machines working in a rectangular Cartesian coordinate system, machines with serial kinematic structure.