VIRTUAL PROTOTYPING OF MACHINE TOOLS
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.

© Prof. Ing. Peter Demč, CSc.
Assoc. Prof. Ing. Jozef Svetlík, PhD.

VIRTUAL PROTOTYPING OF MACHINE TOOLS

Reviewers:
prof. Ing. Ildikó Maňková, CSc.
prof. Ing. Slavko Pavlenko, CSc.

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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 methodologies 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.

The authors express their thanks to the reviewers, namely Prof. Ing. Jozef Pilc, CSc. from the Faculty of Mechanical Engineering of the University of Žilina, Prof. Ing. Ildikó Maňková, CSc. from the Faculty of Mechanical Engineering of the Technical University in Košice and Prof. Ing. Slavko Pavlenko, CSc. from the Faculty of Production Technology of the Technical University in Košice, based in Prešov, for a careful reading of the manuscript of the monograph and valuable reminders and advice that contributed to the quality of the publication and will be an inspiration to us for the future.

At this point, we would also like to thank our families for their quiet support and the incongruous tolerance they have given us to work on the publication.

Košice November 25, 2017

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_q marking the examined point of model body after rotation around the axis X_i
A_s marking the examined point of model body after rotation around the axis Y_i
A_y 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_{max} (mm) maximum workpiece width
B_{min} (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_{i} (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_{max} (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_r (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
Virtual Prototyping of Machine Tools

- \( f_Z \) (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
- \( g_{13} \) (mm): dimension from machine design
- \( H_w \) (mm): workpiece height
- \( H_{\text{max}} \) (mm): maximum workpiece height
- \( H_{\text{min}} \) (mm): minimum workpiece height
- \( H \) (mm): dimension from machine design
- \( H_1 \) (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
- \( h \) (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
- \( L_{\text{opt}} \) (mm): optimal distance between the spindle bearings
- \( L_f \) (mm): distance between the spindle bearings
- \( L_w \) (mm): workpiece length
- \( L_{\text{max}} \) (mm): maximum workpiece length
- \( L_{\text{min}} \) (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
- \( 0_b \): origin of the workpiece coordinate system
<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$p$</td>
<td>(mm) dimension from machine design</td>
</tr>
<tr>
<td>$R_p$</td>
<td>(mm) radius of the semi-finished product</td>
</tr>
<tr>
<td>$R_{\text{max}}$</td>
<td>(mm) maximum really machined radius</td>
</tr>
<tr>
<td>$R_{\text{min}}$</td>
<td>(mm) minimum really machined radius</td>
</tr>
<tr>
<td>$r_e$</td>
<td>(mm) the tip radius of the cutting wedge</td>
</tr>
<tr>
<td>$S_i$</td>
<td>coordinate system of $T_i$ model body</td>
</tr>
<tr>
<td>$T_i$</td>
<td>designation of the model body (the index determines its order)</td>
</tr>
<tr>
<td>$t$</td>
<td>(s) time - general designation</td>
</tr>
<tr>
<td>$t_{\text{min}}$</td>
<td>(min) time in minutes</td>
</tr>
<tr>
<td>$t_{\text{s}}$</td>
<td>(s) time in seconds</td>
</tr>
<tr>
<td>$u_i(t)$</td>
<td>(mm) instantaneous path of the model body $T_i$ in the direction of the $X_i$ axis</td>
</tr>
<tr>
<td>$v_c$</td>
<td>(m-min$^{-1}$) cutting speed</td>
</tr>
<tr>
<td>$v_{\text{vX}}$</td>
<td>(mm-min$^{-1}$) feed speed in the direction of the $X_i$ axis</td>
</tr>
<tr>
<td>$v_{\text{vY}}$</td>
<td>(mm-min$^{-1}$) feed speed in the direction of the $Y_i$ axis</td>
</tr>
<tr>
<td>$v_{\text{vZ}}$</td>
<td>(mm-min$^{-1}$) feed speed in the direction of the $Z_i$ axis</td>
</tr>
<tr>
<td>$v_{i}(t)$</td>
<td>(mm) instantaneous path of the model body $T_i$ in the direction of the $Y_i$ axis</td>
</tr>
<tr>
<td>$w_{i}(t)$</td>
<td>(mm) instantaneous path of the model body $T_i$ in the direction of the $Z_i$ axis</td>
</tr>
<tr>
<td>$X$</td>
<td>general designation of the axis of the coordinate system of the machine tool</td>
</tr>
<tr>
<td>$X_i$</td>
<td>designation of the axis of the coordinate system of the model body $T_i$</td>
</tr>
<tr>
<td>$X_{\text{uvw}}$</td>
<td>designation the $X_i$ axis after rotation of the model body $T_i$ around the $Y_i$ axis</td>
</tr>
<tr>
<td>$X_{\text{uvr}}$</td>
<td>designation the $X_i$ axis after rotation of the model body $T_i$ around the $Z_i$ axis</td>
</tr>
<tr>
<td>$X_{\text{vp}}$</td>
<td>designation the $X_i$ axis after displacement of the model body $T_i$</td>
</tr>
<tr>
<td>$x_i$</td>
<td>(mm) coordinate on the $X_i$ axis</td>
</tr>
<tr>
<td>$x_{ik}$</td>
<td>(mm) $x$-coordinate of point $A_k$ in the coordinate system of the model body $T_i$</td>
</tr>
<tr>
<td>$x_{0,i+1}$</td>
<td>(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</td>
</tr>
<tr>
<td>$Y$</td>
<td>general designation of the axis of the coordinate system of the machine tool</td>
</tr>
<tr>
<td>$Y_i$</td>
<td>designation of the axis of the coordinate system of the model body $T_i$</td>
</tr>
<tr>
<td>$Y_{\text{vpr}}$</td>
<td>designation the $Y_i$ axis after rotation of the model body $T_i$ around the $X_i$ axis</td>
</tr>
<tr>
<td>$Y_{\text{vpr}}$</td>
<td>designation the $Y_i$ axis after rotation of the model body $T_i$ around the $Z_i$ axis</td>
</tr>
<tr>
<td>$Y_{\text{p}}$</td>
<td>designation the $Y_i$ axis after displacement of the model body $T_i$</td>
</tr>
<tr>
<td>$y_i$</td>
<td>(mm) coordinate on the $Y_i$ axis</td>
</tr>
<tr>
<td>$y_{ik}$</td>
<td>(mm) $y$-coordinate of point $A_k$ in the coordinate system of the model body $T_i$</td>
</tr>
</tbody>
</table>
| $y_{0,i+1}$ | (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 $T_i$

$Z_{iwp}$  
designation the $Z_i$ axis after rotation of the model body $T_i$ around the $X_i$ axis

$Z_{iwi}$  
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 $T_i$

$z_i$  
number of teeth of the cutter

$z_{ik}$ (mm)  
$z$-coordinate of point $A_i$ 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

$\Theta$ (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

$\alpha_0$ (°)  
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

$\gamma_0$ (°)  
tool forehead angle in the orthogonal plane

$\kappa_i$ (°)  
age of the adjusting of the main cutting edge

$\lambda_i$ (°)  
age of inclination of the cutting edge

$\Delta x_i$ (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

$\Delta x_{i1}$ (mm)  
deviation of the position of the point $A$ in the $X_i$ direction after the $T_i$ model body rotates around the $Y_i$ axis

$\Delta x_{i2}$ (mm)  
deviation of the position of the point $A$ in the $X_i$ direction after the $T_i$ model body rotates around the $Z_i$ axis

$\Delta y_i$ (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

$\Delta y_{i1}$ (mm)  
deviation of the position of the point $A$ in the $Y_i$ direction after the $T_i$ model body rotates around the $X_i$ axis

$\Delta y_{i2}$ (mm)  
deviation of the position of the point $A$ in the $Y_i$ direction after the $T_i$ model body rotates around the $Z_i$ axis

$\Delta z_i$ (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

$\Delta z_{i1}$ (mm)  
deviation of the position of the point $A$ in the $Z_i$ direction after the $T_i$ model body rotates around the $X_i$ axis

$\Delta z_{i2}$ (mm)  
deviation of the position of the point $A$ in the $Z_i$ direction after the $T_i$ model body rotates around the $Y_i$ axis

$\delta_{i1}$ (mm)  
displacement of the origin of the coordinate system of the model body $T_i$ in the $X_i$ axis direction

$\delta_{i2}$ (mm)  
displacement of the origin of the coordinate system of the
USED DESIGNATIONS

δzi (mm) displacement of the origin of the coordinate system of the model body Ti in the Zi axis direction

ϕ(t) (rad) angular inaccuracy - rotation of the model body Ti around the Xi axis

ϕi (rad) angular inaccuracy - rotation of the workpiece around the Xi axis

τ(t) (rad) angular inaccuracy - rotation of the model body Ti around the Yi axis

τi (rad) angular inaccuracy - rotation of the workpiece around the Yi axis

ψi (rad) angular inaccuracy - rotation of the model body Ti around the Zi axis

ψi (rad) angular inaccuracy - rotation of the workpiece around the Zi axis

ωi (rad·s⁻¹) angular spindle speed

MATRICES AND VECTORS DESIGNATION

[E] identity matrix

{Ki+1,i} starting position vector of the model body Ti+1 coordinate system in the Ti model body coordinate system

{0} null vector

[R+1,i(t)] rotational motion transformation matrix of the model body Ti+1 relative to the Ti model body

[1XR+1,i(t)] rotational motion transformation matrix of the model body Ti+1 relative to the Ti model body around the axis Xi in any sense

[1YR+1,i(t)] rotational motion transformation matrix of the model body Ti+1 relative to the Ti model body around the axis Yi in any sense

[2ZR+1,i(t)] rotational motion transformation matrix of the model body Ti+1 relative to the Ti model body around the axis Zi in any sense

[2Z-R+1,i(t)] rotational motion transformation matrix of the model body Ti+1 relative to the Ti model body around the axis Zi in a positive sense

[2Z-R+1,i(t)] rotational motion transformation matrix of the model body Ti+1 relative to the Ti model body around the axis Zi in a negative sense

{ri(t)} position vector of any point of the model body Ti+1 in the coordinate system of the model body Ti

{ri+1(t)} position vector of any point of the model body Ti+1 in his coordinate system

{ri+δ} position vector of any point on the model body Ti after changing its position due to linear positional inaccuracies

{i rites} position vector of any point of the model body Ti+1 in the
coordinate system of the model body $T_i$ in the position at the beginning of machining

$\{r_s\}$

tool contact point position vector in the tool carrier coordinate system (model body $T_s$)

$\{r_0(t)\}$

tool contact point position vector in the workpiece coordinate system (model body $T_0$)

$\{T_{i+1,0}(t)\}$

the linear motion transformation vector of the model body $T_{i+1}$ relative to the $T_i$ model body

$\{^X T_{i+1,0}(t)\}$

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

$\{^Y T_{i+1,0}(t)\}$

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

$\{^Z T_{i+1,0}(t)\}$

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

$\{\Delta(t)\}$

the resulting position inaccuracy vector of the $T_i$ model body

$\{\Delta(t)\}$

the resulting position inaccuracy vector of the model body $T_i$ taking into account the influence of the linear inaccuracies of its position

$\{\Delta_0\}$

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.