

**TECHNICAL UNIVERSITY OF KOŠICE
FACULTY OF MECHANICAL ENGINEERING**

Prof. Ing. Peter Demeč, CSc. – Assoc.Prof. Ing. Tomáš Stejskal, PhD.

**VIRTUAL PROTOTYPING AND EXPERIMENTAL
VERIFICATION OF MACHINE TOOLS ACCURACY**

The monograph aims to acquaint the scientific and professional public with the results of numerical and experimental research into the design properties of machine tools in terms of their impact on their working accuracy. The publication draws on the results of the authors' own research activities within the grant project KEGA no. 025TUKE-4/2019: Integrated training laboratory for virtual prototyping and experimental verification of machine tool accuracy and was supported also by the Slovak Research and Development Agency under the Contract no. APVV-18-0413

© Prof. Ing. Peter Demeč, CSc.
Assoc.Prof. Ing. Tomáš Stejskal, PhD.

VIRTUAL PROTOTYPING AND EXPERIMENTAL VERIFICATION OF MACHINE TOOLS ACCURACY

Reviewers:

Prof. h. c. Prof. Ing. Karol Velíšek, CSc.
Prof. Ing. Jozef Pilc, CSc.
Prof. Ing. Slavko Pavlenko, CSc.

ISBN 978-3-96595-013-9

CONTENTS

FOREWORD	5
USED DESIGNATIONS	6
1. THEORETICAL FUNDAMENTALS	13
1.1 RELATIVE MOVEMENTS OF TWO MODEL BODIES OF MACHINE TOOL	14
1.1.1 Rotational movements of two model bodies	14
1.1.2 Linear movements of two model bodies	17
1.1.3 Generalization of equations for the movements of two model bodies	20
1.2 MATHEMATICAL MODEL OF IDEAL TOOL TRAJECTORY	21
2. MODELING OF STATIC CHARACTERISTICS OF MACHINE TOOLS	26
2.1 MATHEMATICAL MODEL OF INACCURACIES BY THE MACHINING	26
2.1.1 Influence of the position inaccuracy of the model body T_i on the tool position in the coordinate system of the examined body	26
2.1.2 Influence of the position inaccuracy of the model body T_i on the tool position in the workpiece coordinate system	32
2.1.3 Mathematical model of the resulting inaccuracy of machining	33
2.2 METHODOLOGY OF CREATING COMPUTATIONAL MODELS FOR MODELING THE TOOL TRAJECTORY	34
2.3 MACHINE - TOOL - WORKPIECE SYSTEM INACCURACIES	47
2.3.1 Spindle node inaccuracies.....	47
2.3.1.1 <i>Throwing of the spindle front end</i>	47
2.3.1.2 <i>Static deformations of the spindle node</i>	49
2.3.1.3 <i>Bending vibrations of the spindle</i>	49
2.3.1.4 <i>Spindle positioning inaccuracies</i>	50
2.3.1.5 <i>The resulting inaccuracy of the spindle node</i>	50
2.3.2 Inaccuracies of the basic parts of the machine frame.....	50
2.3.3 Inaccuracies of guide systems.....	53
2.3.4 Other sources of inaccuracies.....	55
3. MODELING THE DYNAMIC PROPERTIES OF MACHINE TOOLS	57
3.1 PRINCIPLES FOR DESIGNING DYNAMIC CALCULATION MODELS	58
3.2 CALCULATION OF PARAMETERS OF ELEMENTS OF THE DYNAMIC COMPUTATIONAL MODEL	66
3.3 DYNAMIC COMPUTATIONAL MODELS OF MACHINE TOOL.....	70
3.3.1 Discrete models	71
3.3.2 Continuous models	75
4. VIRTUAL MACHINING – PRACTICAL SOLUTIONS	95
4.1 VIRTUAL MACHINING ON THE SMALL CENTRE LATHE.....	95
4.2 VIRTUAL MACHINING ON THE HORIZONTAL MACHINING CENTRE	110
4.3 VIRTUAL MACHINING ON A VERTICAL MACHINING CENTRE GANTRY CONSTRUCTION	135

5. EXPERIMENTAL RESEARCH OF STATIC AND DYNAMIC PROPERTIES OF MACHINE TOOLS.....	162
5.1 ANALYSIS OF VIBRATION PROCESSES	163
5.2 ROOT CAUSES OF VIBRATIONS ON MACHINE TOOLS	177
5.3 MEASUREMENT OF STATIC STIFFNESS OF MACHINE TOOLS	181
5.4 EXPERIMENTS FOCUSED ON THE SPECIFIC ANALYSIS OF THE STATIC STIFFNESS OF MACHINE TOOLS	186
5.4.1 Static stiffness measurement during continuous positioning of a three-axis milling machine [45]	186
5.4.1.1 Measurement of static stiffness by classical method	189
5.4.1.2 Alternating measurement of static stiffness under continuous load during displacement table and without load during table movement - measurement of starting stiffness	190
5.4.1.3 Repeated loading of the table position with small reciprocating feeds - measurement of onsetting stiffness	191
5.4.2 Continuous measurement of the stiffness of a three-axis milling machine depending on the loading speed and the relative position of the machine components [35], [45]	194
5.4.3 Measurement of counter static stiffness as a function of the clamping force of the beam-vice clamp [44]	205
5.4.3.1 The first test experiment of double-sided loading	208
5.4.3.2 Alternating load experiments with control classical load and change of degree of stiffness of beam clamping	210
5.4.3.3 Monitoring of residual deformations after unloading in the alternating load method	212
5.5 DISCUSSION ON EXPERIMENTAL RESULTS OF MEASUREMENT OF STATIC STIFFNESS OF MACHINES	213
5.6 CONSTRUCTIONAL PHILOSOPHIES OF MACHINE TOOLS IN TERMS OF STATIC AND DYNAMIC DEPENDENTS	215
REFERENCES	222

PREFACE

We have prepared the presented scientific monograph in order to acquaint the general scientific and professional public with some research results with the results of numerical and experimental research of the properties of machine tool construction in terms of their impact on their working accuracy. Identifying the influences of the machining process itself, as well as the influences of the design properties of the machine tool, will make it possible to predict and subsequently optimize its design in terms of its achieved working accuracy. The practical importance of virtual machining and experimental research in this area is primarily in reducing financial costs and speeding up machine design without the need to produce a physical prototype. Using simulation models, it is possible to repeatedly analyze the weak points of the machine design, determine the effects of individual components of the machine on its properties and optimize them, but also take into account ergonomic and other requirements.

The publication draws on the results of the authors' own research activities within the grant project KEGA no. 025TUKE-4/2019: Integrated training laboratory of virtual prototyping and experimental verification of machine tools accuracy and from previous grant research projects, partial results of which have been published in works listed in the bibliography. Developed and verified methodologies of virtual machining, mathematical simulations and experiments are developed by the scientific field of Production Machines and Equipment and can be used in industrial practice in existing, respectively potential machine tool manufacturers.

The authors thank the reviewers, namely Prof. h. c. Prof. Ing. Karol Velíšek, CSc. from the Faculty of Materials Science and Technology in Trnava, Prof. Ing. Jozef Pilc, CSc. from the Faculty of Mechanical Engineering of the University of Žilina and Prof. Ing. Slavko Pavlenko, CSc. from the Faculty of Production Technologies of the Technical University in Košice based in Prešov for careful reading of the manuscript of the monograph and their valuable comments and advice, which contributed to the improvement of the publication and will be an inspiration for us in the future.

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

Košice, October 31, 2021

Authors