Lecture Notes in Production Engineering

Christian Brecher
Manfred Weck

Machine Tools Production Systems 2

Design, Calculation and Metrological Assessment

Springer

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Foreword for the Machine Tools and Manufacturing Systems Compendium

Machine tools are among the most important means of production in the metalworking industry. The current high standard of living in industrialized nations would be inconceivable had this category of machinery not been developed. The Federal Republic of Germany is a world leader in the production of machine tools. In the Federal Republic of Germany, approximately 7.4% of the total mechanical engineering production volume comes from the machine tool industry and 7.0% of those employed in mechanical engineering work in the machine tool industry (German Machine Tool Builder's Association (VDW), as of 2018).

The application areas for machine tools are just as diverse as their structural design and degree of automation. According to the technological processes, this extensive field ranges from machine tools for primary forming and forming, through machine tools for cutting (including chip-removing machine tools) to joining machines. These machines have varying degrees of automation and more or less flexibility depending on the workpieces to be machined and the lot sizes. As a result, single-purpose and special machine tools as well as universal machines with an extensive range of potential applications are available on the market.

Due to the increasing demands on performance and accuracy, the designer of these machines must ensure an optimum design of the individual machine components. To do this, the designer must have a comprehensive knowledge of the relationships between the physical properties of the components and of the machine elements. Today, the designer can provide computer-aided designs using a substantial library of programs. The criteria that determine performance and accuracy such as the geometric, kinematic, static, dynamic, thermoelastic and acoustic properties can be evaluated through metrological analyses and objective assessment methods. The specific improvements necessary can then be put in place.

The continuing tendency toward the automation of machine tools has led to a broad spectrum of control system alternatives. In recent years, developments in electrical engineering, electronics and software technology have had a significant influence on machine control systems. Microprocessors and process computers can now provide control-engineering solutions that were previously unthinkable. The mechanization and automation efforts have also included the areas of material transport and machine feeding. Considerations in this area led to transfer lines in mass production and to flexible manufacturing cells and systems in small and medium series manufacturing.

The three volumes that make up this series on the subject of Machine Tools and Manufacturing Systems are aimed at both university students majoring in production engineering and all practicing professionals who must keep pace with the increasingly complex material covering this branch of mechanical engineering. In addition, these volumes will help the user select suitable machines and the relevant control systems. The machine manufacturer is provided with ways of producing the best layout of the machine components, drive systems and control systems together with options for specific improvements based on metrological analyses and objective assessment methods.

The content of the complete work is closely based on the Machine Tools lectures at the RWTH Aachen University and is structured as follows:

Volume 1: Machine tools—Machine types and application areas,
Volume 2: Machine tools—Design, calculation and metrological assessment,
Volume 3: Machine tools—Mechatronic systems, control engineering and automation.

Christian Brecher
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July 2021

Foreword to Volume 2

The first part of this volume assists the designer in the selection and simulation of machine tool structures and components in terms of their static, dynamic and thermoelastic behavior. Initially, consideration is given to the structural components and machine tool installations. This includes a description of the effects of conventional and alternative materials on the machine properties. Computer-aided calculation methods and optimization approaches form the basis of an optimal design of structural components. This is followed by an assessment of the hydraulic systems and components that determine the performance and accuracy, such as guide systems, bearing arrangements and feed systems, as well as an introduction to the methods for designing such systems. A separate chapter deals with the gearboxes that are still used in machine tools today. Aspects of industrial design are also becoming increasingly important. A designer must therefore be very familiar with the current guidelines on machine design. Both are covered in detail in the revised edition.

The second part of this volume deals with the metrological investigation and assessment of the entire machine tool or its components with respect to the properties discussed in the first part of this volume. After a discussion of the basic principles of metrology, the conventional and newer measuring devices and measuring methods used to measure distances, angles, forces, speeds, accelerations, temperatures and sound power are introduced. The subsequent chapters describe the procedure for measuring the geometric, kinematic, static, dynamic, thermoelastic and acoustic behavior of machine tools. A separate chapter covers the assessment of machine accuracy using manufactured test workpieces. The interaction between the process and the machine is also dealt with separately. This is particularly important for the vibration behavior (chattering) of cutting machine tools. Methods and measures for assessing and improving the behavior of machine tools are presented for all of the relevant properties.

The content of this volume is structured as follows:

Following a short introduction (*Chapter 1*), which outlines the designer's tools, *Chapter 2* briefly describes the general demands made on the frame and frame components.

Next, *Chapter 3* provides the reader with detailed information on the design and layout criteria for static, dynamic and thermal loads. Today, computer-aided processes and powerful calculation programs are used throughout the design and development process. For this reason, the mathematical basics of the Finite Element Method (FEM) are explained and their areas of application in the machine tool industry are illustrated using examples of sizing, shape and topology optimization. Finally, a separate section deals with conventional materials for frame components and making the best use of materials in machine design. The alternative materials of cement concrete, reaction resin concrete and fiber-reinforced plastic are also discussed in this section.

The installation and foundations of machine tools are covered in *Chapter 4*. While smaller machine tools are often mounted directly on the factory floor or floor slabs, medium-sized and large, heavy machine tools without adequate inherent stiffness require their own foundation design. Mounting arrangements with vibration isolation are also frequently necessary. The components of different machine installations are compared and the static and dynamic aspects of foundation design are also discussed.

The drive elements for generating the main working motions are just as important for the performance of machine tools as careful design of the frame components. As electrical design and, with it, the description of electromechanical drives, are part of Volume 3 of this Compendium, *Chapter 5* discusses purely hydraulic drive elements and concepts in detail.

The guide systems, bearing arrangements and feed systems within the force flux are particularly significant for the machining accuracy of a machine tool. This topic is comprehensively covered in *Chapter 6*. After explaining the basics of tribology, the function and operation of hydrodynamic plain guide systems and plain bearings are presented as these guiding principles are still being used in the machine tool industry. Hydrostatic plain guide systems and plain bearings are also discussed with the focus being on the layout and design of these types of bearings. Examples are used to illustrate their use in precision machine tools. After this, high-precision and

high-speed machining are covered in a discussion of important aerostatic bearings and guides as well as electromagnetic bearings. Due to their very wide use and significance in practice, rolling element guide systems and bearings are discussed in particular detail. After presenting the structural design of rolling element guide systems, the use of rolling element bearings in spindle-bearing systems is discussed in detail. New designs of rolling element bearings for high-speed main spindles are also presented. Design principles, layout criteria and the necessary calculation methods are presented through numerous examples. Ball screw drives and roller screw drives are presented as conventional systems for transmitting feed motions along linear axes. The important subjects of lubricating and sealing the individual machine components are covered separately in each subsection. Chapter 6 closes with possible protection measures for guide elements and options for covering guideways.

Transmissions are also used today to supplement the components and main drives of machine tools required to produce traversing movements and machining. For this reason, *Chapter 7* presents the reader with the essential basic principles and design criteria for uniform and non-uniform transmissions.

Last but not least, the demand from the modern machine tool industry for improvements in performance characteristics has led to a standalone chapter which covers the part industrial design plays in the development process (*Chapter 8*). This includes a discussion of the machine panels, the ergonomic design and configuration of the controls, and the place of the design process in development. The current guidelines on machine design are also covered in detail.

Having covered all the important aspects of machine tool design and simulation, *Chapter 9* provides an overview of the measuring devices and measuring methods needed to assess machine tools. The measurement procedures described in the subsequent chapters refer back to this section.

Deviations in the actual relative motion (or the actual position) between the tool and the workpiece from the target relative motion (or the target position) have a significant influence on the dimensional accuracy of the workpieces produced on machine tools. The procedure for measuring these geometric and kinematic deviations is described in *Chapter 10*.

Chapter 11 discusses the measurement technology and evaluation methods for examining machine deformation under static loads (workpiece weight forces and process forces).

Chapter 12 deals with the measurement of geometric and kinematic machine deviations due to the effects of thermal deformation. The thermoelastic behavior is an increasingly important factor in the accuracy achievable by machine tools, particular against the background of constantly increasing cutting and feed rates and axis accelerations as well as the associated heat influx to the machine structure. This development is taken into consideration by the introduction of new measuring methods for the simple assessment of the thermoelastic structural deformation in machine tools. Sensor-aided correction methods are also discussed.

Vibration phenomena in machine tools are usually linked to the dynamic compliance behavior of the machine structure. *Chapter 13* discusses this topic in detail. This includes, in particular, investigation of the dynamic behavior, the theoretical bases of measurement, the relationships during the emergence of chatter vibrations and the options for improving dynamic machine behavior through the selection of suitable process parameters.

Chapter 14 illustrates indirect methods of measuring geometric and kinematic machine characteristics using machining tests. In these tests, the machine quality is determined by evaluating the dimensions of test workpieces. The significance of capability studies for the acceptance of special-purpose machines and the procedures carried out during these studies are explained and a guideline created for this purpose is presented.

Finally, *Chapter 15* discusses the acoustic behavior of machine tools which is a very important acceptance criterion. Following an introduction to the basic concepts of acoustics, options for the measurement, assessment and analysis of noise are illustrated and current measurement guidelines presented. Low-noise machine design is also covered, a factor that is becoming increasingly important in view of the humanization of the workplace. The various sources of machine noise are described and specific structural measures for noise reduction are explained.

This edition is the translation of the German ninth edition and was revised with the cooperation of my research assistants. My sincere thanks go to all those involved for their enormous commitment. I particularly wish to thank Dr.-Ing. Simo Schmidt for coordinating and organizing the basic revision of the ninth edition.

I also wish to thank most sincerely the companies who provided the illustrations for this volume.

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