Lecture Notes in Production Engineering

Berend Denkena
Ferdinand Hollmann
Editors

Process Machine Interactions

Predicition and Manipulation of Interactions between Manufacturing Processes and Machine Tool Structures

Springer

Lecture Notes in Production Engineering

For further volumes:
http://www.springer.com/series/10642

Berend Denkena and Ferdinand Hollmann (Eds.)

Process Machine Interactions

Predicition and Manipulation of Interactions between Manufacturing Processes and Machine Tool Structures

Springer

Editors
Prof. Dr.-Ing. Berend Denkena
Leibniz Universität Hannover
Coordinator of Priority Program 1180
Garbsen
Germany

Dr.-Ing. Ferdinand Hollmann
German Research Foundation
Program Director Engineering Science
Bonn
Germany

ISSN 2194-0525
e-ISSN 2194-0533
ISBN 978-3-642-32447-5
e-ISBN 978-3-642-32448-2
DOI 10.1007/978-3-642-32448-2
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012947591

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The Priority Program 1180 "Prediction and Manipulation of Interactions between Structure and Process" was funded by the German Research Foundation DFG from 2005 to 2012. It was initiated by researchers from the German Academic Society for Production Engineering WGP and accompanied by a working group on process machine interaction within the International Academy for Production Engineering CIRP. The priority program dealt with the modeling and prediction of interactions between machine structures and manufacturing processes in technical systems. The objective was a sound reproduction of these interactions and a basic understanding of the acting inter-relationships in order to be able to specifically influence and plan manufacturing processes in the future. The understanding of process machine interactions is a big issue in modern production technology. These interactions can be the cause of erroneous processes, which directly lead to undesired quality problems. To cope with rising quality demands and the ongoing need to increase production efficiency in the future, 20 interdisciplinary research projects were funded for a 6 years period by the DFG. In these projects, models and simulation tools were developed for a variety of manufacturing technologies, such as cutting, grinding or forming. Due to the intensive collaboration of researchers from different disciplines, such as Production Engineering, Mechanical Engineering or Mathematics, it was possible to gain a deep understanding of process machine interactions. In addition, detailed models and efficient simulation techniques to predict the interactions within a reasonable calculation time were developed.

Process-machine-interactions have become a central research topic in production engineering within the last years, not only in academic research but also in industrial companies. Machine tool builders are expanding the use of simulation methods to design machine tools, particularly considering process-machine-interactions. According to the resulting demand for access to research results and exchange, a series of International Conferences on Process Machine Interactions has been successfully implemented with a steadily increasing number of participants. The Priority Program 1180 contributed to this important research topic by providing elementary experimental methods and mathematically verified computation models.

This book consists of the four parts “Basics”, “Grinding”, “Cutting” and “Forming”. Part I “Basics” gives an overview of the applied and developed methods in Measuring Technology, Modeling and Simulation and Mathematical Methods. The following 3 parts “Grinding”, “Cutting” and “Forming” contain the main scientific results and modeling approaches of all 20 research projects, covering a wide range of topics, e. g. tool grinding, milling and deep drawing. Despite the large number of different manufacturing methods investigated by the projects, some topics, such as dynamic self-excitation of machine tools, known as “chatter vibration”, the static deflection of machine tool parts due to the acting process forces or the influence of thermal effects, were addressed by nearly all of the research projects.

Prof. Dr.-Ing. Berend Denkena
Leibniz Universität Hannover
Coordinator of Priority Program 1180

Dr.-Ing. Ferdinand Hollmann
German Research Foundation
Program Director Engineering Science

Contents

Part I: Basics

Part II: Grinding

Part III: Cutting

Part IV: Forming

List of Authors

Abele, E.
Technische Universität Darmstadt, Institute of Production Management, Technology and Machine Tools

Andres, M.
Leibniz Universität Hannover, Institute for Applied Mathematics

Aurich, J. C.
University of Kaiserslautern, Institute for Manufacturing Technology and Production Systems

Bach, F.-W.
Leibniz Universität Hannover, Institute of Material Science

Bauer, J.
Technische Universität Darmstadt, Institute of Production Management, Technology and Machine Tools

Behrens, B.-A.
Leibniz Universität Hannover, Institute of Metal Forming and Metal Forming Machine Tools

Biermann, D.
Technische Universität Dortmund, Faculty of Mechanical Engineering, Institute of Machining Technology

Blum, H.
Technische Universität Dortmund, Faculty of Mathematics (LS X)

Bouabid, A.
Universität Erlangen-Nürnberg, Chair of Applied Mechanics

Bouguecha, A.
Leibniz Universität Hannover, Institute of Metal Forming and Metal Forming Machine Tools

Brandt, C.
University of Bremen, Center for Industrial Mathematics

Brecher, C.
RWTH Aachen University, Laboratory of Machine Tools and Production Engineering, Chair of Machine Tools

Brinksmeier, E.
University of Bremen, Foundation Institute of Materials Science, Laboratory of Precision Machining

Britz, R.
Technische Universität München, Institute of Applied Mechanics, Department of Mechanical Engineering

Carstensen, C.
Humboldt University of Berlin, Department of Mathematics

Czora, M.
Leibniz Universität Hannover, Institute of Metal Forming and Metal Forming Machine Tools

De Payrebrune, K.M.
Technische Universität Bergakademie Freiberg, Institute for Machine Elements, Design and Manufacturing

Deichmueller, M.
Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools

Denkena, B.
Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools

Druwe, T.
Fraunhofer Institute for Machine Tools and Forming Technology

Eberhard, P.
Universität Stuttgart, Institute of Engineering and Computational Mechanics

Engel, U.
Universität Erlangen-Nürnberg, Chair of Manufacturing Technology

Esser, M.
RWTH Aachen University, Laboratory of Machine Tools and Production Engineering

Franzke, M.
RWTH Aachen University, Institute of Metal Forming

Friedmann, M.
Technische Universität Darmstadt, Department of Computer Science, Simulation, Systems Optimization and Robotics Group

Gaugele, T.
Universität Stuttgart, Institute of Engineering and Computational Mechanics

Großmann, A.
Technische Universität Dresden, Institute of Machine Tools and Control Engineering

Hardtmann, A.
Technische Universität Dresden, Institute of Machine Tools and Control Engineering

Heinisch, D.
Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools

Heisel, U.
Universität Stuttgart, Institute for Machine Tools

Hellfritzsch, U.
Fraunhofer Institute for Machine Tools and Forming Technology

Hemker, T.
Technische Universität Darmstadt, Department of Computer Science, Simulation, Systems Optimization and Robotics Group

Hermes, R.
RWTH Aachen University, Laboratory of Machine Tools and Production Engineering, Chair of Machine Tools

Hirt, G.
RWTH Aachen University, Institute of Metal Forming

Hömberg, D.
Weierstrass Institute, Berlin

Kiliclar, Y.
RWTH Aachen University, Institute of Applied Mechanics

Kirsch, B.
University of Kaiserslautern, Institute for Manufacturing Technology and Production Systems

Kleiner, M.
Technische Universität Dortmund, Institute of Forming Technology and Lightweight Construction

Klocke, F.
RWTH Aachen University, Laboratory of Machine Tools and Production Engineering, Chair of Manufacturing Technology

Krause, A.
University of Bremen, Laboratory for Precision Machining

Kriechenbauer, S.
Technische Universität Dresden, Institute of Machine Tools and Control Engineering

Krimm, R.
Leibniz Universität Hannover, Institute of Metal Forming and Metal Forming Machine Tools

Kröger, M.
Technische Universität Bergakademie Freiberg, Institute for Machine Elements, Design and Manufacturing

Kroiß, T.
Universität Erlangen-Nürnberg, Chair of Manufacturing Technology

Lahl, M.
Fraunhofer Institute for Machine Tools and Forming Technology

Laurischkat, R.
Ruhr-University Bochum, Chair of Production Systems

Löser, M.
Technische Universität Dresden, Institute of Machine Tools and Control Engineering

Maaß, P.
University of Bremen, Center for Industrial Mathematics

Mahr, F.
Technische Universität Berlin, Institute of Machine Tools and Factory Management

Maier, T.
Technische Universität München, Institute for Machine Tools and Industrial Management, Department of Mechanical Engineering

Maischak, M.
Leibniz Universität Hannover, Institute for Applied Mathematics

Matthias, T.
Leibniz Universität Hannover, Institute of Metal Forming and Metal Forming Machine Tools

Meier, H.
Ruhr-University Bochum, Chair of Production Systems

Milbrandt, M.
Fraunhofer Institute for Machine Tools and Forming Technology

Neugebauer, R.
Fraunhofer Institute for Machine Tools and Forming Technology

Niebsch, J.
Johann Radon Institute for Computational and Applied Mathematics, Austrian Academy of Sciences

Penter, L.
Technische Universität Dresden, Institute of Machine Tools and Control Engineering

Pischan, M.
Technische Universität Darmstadt, Institute of Production Management, Technology and Machine Tools

Puchhala, S.
RWTH Aachen University, Institute of Metal Forming

Rademacher, A.
Technische Universität Dortmund, Faculty of Mathematics (LS X)

Ramlau, R.
Johannes Kepler University Linz, Industrial Mathematics Institute

Rasper, P.
Technische Universität Berlin, Institute of Machine Tools and Factory Management

Reese, S.
RWTH Aachen University, Institute of Applied Mechanics

Reinl, C.
Technische Universität Darmstadt, Department of Computer Science, Simulation, Systems Optimization and Robotics Group

Rott, O.
Weierstrass Institute, Berlin

Scheidler, A. V.
Technische Universität Dortmund, Faculty of Mechanical Engineering, Institute of Machining Technology

Schiller, S.
Fraunhofer Institute for Machine Tools and Forming Technology

Schröder, A.
Humboldt University of Berlin, Department of Mathematics

Schwarz, F.
Technische Universität München, Institute for Machine Tools and Industrial Management, Department of Mechanical Engineering

Shi, Y.
Technische Universität Berlin, Departments of Mechanics, Chair of Mechatronics and Machine Dynamics

Steinmann, P.
Universität Erlangen-Nürnberg, Chair of Applied Mechanics

Stephan, E. P.
Leibniz Universität Hannover, Institute for Applied Mathematics

Storchak, M.
Universität Stuttgart, Institute for Machine Tools

Tekkaya, A. E.
Technische Universität Dortmund, Institute of Forming Technology and Lightweight Construction

Uhlmann, E.
Technische Universität Berlin, Institute of Machine Tools and Factory Management

Ulbrich, H.
Technische Universität München, Institute of Applied Mechanics, Department of Mechanical Engineering

Vehmeyer, J.
University of Bremen, Center for Industrial Mathematics

von Stryk, O.
Technische Universität Darmstadt, Department of Computer Science, Simulation, Systems Optimization and Robotics Group

von Wagner, U.
Technische Universität Berlin, Departments of Mechanics, Chair of Mechatronics and Machine Dynamics

Wegner, H.
RWTH Aachen University, Laboratory for Machine Tools and Production Engineering

Weinert, K.
Technische Universität Dortmund, Faculty of Mechanical Engineering, Institute of Machining Technology

Weiß, M.
RWTH Aachen University, Laboratory for Machine Tools and Production Engineering

Wiedemann, S.
Humboldt University of Berlin, Department of Mathematics

Wiemer, H.
Technische Universität Dresden, Institute of Machine Tools and Control Engineering

Zaeh, M.
Technische Universität München, Institute for Machine Tools and Industrial Management, Department of Mechanical Engineering

Part I
Basics

Chapter 1
Measurement and Test Techniques

E. Abele, J. C. Aurich, B.-A. Behrens, D. Biermann, C. Brecher,
E. Brinksmeier, M. Czora, B. Denkena, U. Engel, K. Großmann,
U. Heisel, D. Heinisch, R. Hermes, B. Kirsch, F. Klocke, A. Krause,
T. Kroiß, R. Laurischkat, M. Löser, F. Mahr, H. Meier, M. Pischan,
P. Rasper, A. V. Scheidler, M. Storchak, E. Uhlmann, and M. Weiß

Abstract. Nowadays, different measurement and test techniques are used to investigate the interaction between processes and machine tool structures. Machine and workpiece properties are determined after analyzing the individual factors of process metrology, which have an effect on the process. This chapter explains the measurement methods for the structural analysis of the machine tool as well as for manufacturing processes and for the workpiece analysis. In addition, an overview of different measurement and test techniques based on selected examples related to the priority program 1180 is given.

1.1 Introduction

This chapter analyzes the metrological possibilities in order to determine the interaction between process and machine structure. The metrological analysis is subdivided into three main sections: Section 1.2 refers to the structural analysis of the machine tool, section 1.3 to the process analysis and section 1.4 to the analysis of the workpiece. In section 1.2 different measurement and test techniques of the static and the dynamic machine tool behavior, the kinematics and the temperature of machine tools are described. Section 1.3 describes different measurements and test techniques for force, acoustic emission and temperature, whereas section 1.4 describes refuse to surface and geometry assessment. Here, a small imported outline can be obtained and its influence must be analyzed to understand the interaction between process and machine tool structure for specific examples.

1.2 Structural Analysis of Machine Tools

Working precision, performance, environmental behavior and reliability of machine tools affect the quality of manufactured products and the efficiency of the processes significantly. Technological progress in the machine tool industry and the competition pressure to increase productivity ask for higher performance, higher spindle speeds, higher feed rates and longer material removal rates. Hence, new and optimized machine tool structures have to be developed. In addition, due

B. Denkena and F. Hollmann (Eds.): Process Machine Interactions, LNPE, pp. 3–27.
springerlink.com

to significantly increased process loads the demands concerning the working accuracy of the machine tool have increased as well. Thus, apart from performance values like spindle power and speed or feed rate the structural and mechanical properties of the machine tool have to be known in order to assess the accuracy and productivity [1].

To analyze and improve the machine tool behavior it is essential to describe the machine tool characteristics by defined parameters. Despite the good progress in calculating machine tool parameters, the experimental determination of the structural properties is still essential for the parameterization and evaluation of machine tool models. The accuracy of machine tools is primarily affected by deviations at the tool-workpiece interface. Depending on the transmission behavior of the machine tool thermal, static or dynamic loads result in kinematic and geometric deviations from the desired working motions. Therefore, the thermal and dynamic behavior limits the theoretical performance of the machine tool. Due to dynamic instabilities and displacements caused by thermal dilatation the full potential of machines cannot be exploited, which results in a negative impact on the productivity. To ensure the efficiency of machine tools the interactions between process and structure have to be determined. In the following sections, different measurement methods for the analysis of the static, dynamic and thermal structure, their behavior as well as the kinematics are described.

1.2.1 Static Machine Tool Behavior

Static process forces between the workpiece and the tool lead to a static stress on all components and joints of the machine structure included in the flow of force. Thus, the stiffness properties of the machine are the sum of the individual stiffnesses of the concerned elements. The influence of the machine properties on the workpiece is usually of particular interest; hence, investigations of the machine tools stiffness focus on the interface between tool and workpiece. Therefore, the relative displacement between the tool and the workpiece as a result of static process loads has to be investigated. While the process load is usually applied in the three Cartesian coordinate directions, the measured displacements are divided into tilts and deflections. These are each described by a translational and a tilting stiffness matrix, in which the main stiffnesses are located at the principal diagonal of the matrix with the cross stiffnesses next to them. Figure 1.1 shows an example of the analysis of the main stiffness in the z-direction and the tilting about the x-axis by applying a load in z-direction. Machine structures usually show a progressive development of stiffness. After overcoming the clearances in the bearings, the guidance and the screw connections as well as the internal friction in the gears and seals, the stiffness rises with increasing load. Changing contact conditions and internal friction in the joints and contact points cause a hysteresis between loading and load relieving. In this section, the determination of the static stiffness is explained by a press and an industrial robot.

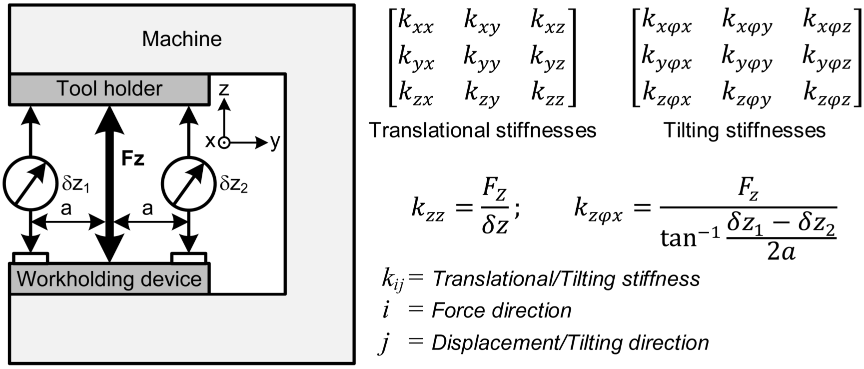

Fig. 1.1 Characterization of static machine compliance (based on [1])

A method to determine the deflection of presses under a static load is described in the standard DIN 55189 “Determination of the ratings of presses for sheet metal working under static load“ for mechanical presses (part 1), as well as for hydraulic presses (part 2) [2]. By means of this method the press is loaded by a hydraulic system, which is applied torque-free by means of a compensation device in z-direction (Fig. 1.2).

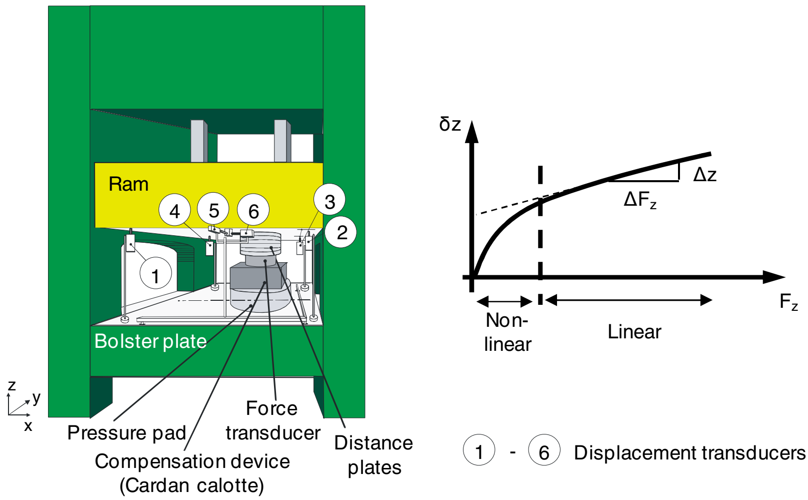

Fig. 1.2 Measurement setup according to the DIN 55189 and resulting displacement development

The standard describes the determination of the deflection in forming direction caused by a centric load and the tilting of the ram as well as its horizontal displacement by an eccentric load. The investigated force-displacement characteristic can be classified into two periods, an initial non-linear displacement and tilting period, which occurs due to bearing clearances, and a period during which the press deflects linear elastically. The relevant static press characteristics such as the horizontal displacement, the tiltings about the x- and y-axis and the stiffnesses, are also defined in DIN 55189 and can be determined by the recorded force-displacement and force-tilting characteristics. The static press characteristics make it possible to compare different types of presses with each other.

In the following paragraph, the determination of the static stiffness of an articulated robot is shown. In Figure 1.3, the measurement setup as well as a typical stiffness in the working space is presented.

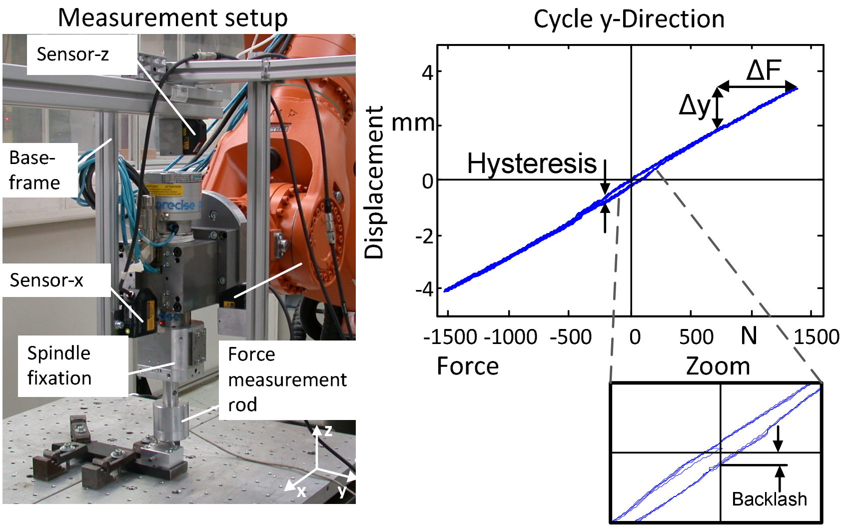

Fig. 1.3 Experimental setup (left) and typical results (right) of an articulated robot

The setup consists of a force measurement rod to apply and detect tensile and compressive forces and laser distance sensors to measure the displacement of the robot due to the force. The difference in the tensile and compressive cycles indicates hysteresis. The backlash amounts to approximately 0.2 mm at the measurement point x = 1,900 mm, y = 0 mm and z = 600 mm in the base coordinate system. Furthermore the measured curves show a slight s-shape due to a non-linear structural behavior. Using the least-squares method a linear slope can be fitted into the measured curve. The gradient of the measured curve then indicates the stiffness.

1.2.2 Dynamic Machine Tool Behavior

The accuracy of a machine tool is determined by the deflection occurring at the contact point between tool and workpiece at the specified target position. Apart from the influences of the static loads, which are described in the previous chapter, the dynamic behavior under varying loads is also a criterion for the performance of a machine tool system. Unbalanced dynamic properties of this system lead to oscillation phenomena, which can result in a poor surface quality of the workpiece, increased machine and tool wear, tool breakage and damage of the machine tool. The latter mentioned damages have to be considered particularly with regard to the occurrence of regenerative chatter oscillations, which increase as a result of the interactions between the dynamic machine tool behavior and process behavior during the machining process [1], [4].

Therefore, the aim of investigating the dynamic machine behavior is to describe possible weak points of the mechanical structure quantitatively using the tools of frequency response measurement and experimental modal analysis [40]. A major application of modal analysis in mechanical engineering is trouble-shooting. As an example, chatter vibrations in machine tools are often caused by structural instabilities, which can be identified using experimental modal analysis techniques. Recently, the investigation of the dynamic machine tool behavior has become more important for the configuration and alignment of simulation models. Nowadays, an important application is the correlation of finite element models with experimental data from modal analysis in order to improve the accuracy of structural dynamic simulations. This is very useful for sensitivity analyses and the prediction of the dynamic behavior due to structural modifications.

The investigation of the dynamic machine tool behavior is always based on the measurement of the frequency-dependent rigidity of the structure [3], [4]. Among signal processing and analog digital conversion (ADC), the required measurement chain can be divided into three major systems. The first is the excitation of the structure. This can be done in several ways. The most commonly used are an attached shaker or a hammer blow. Electromagnetic or electrohydraulic shakers are controlled by a signal generator providing the ability to induce various loads into the structure. These loads can be, for example, sinusoidal, periodic, random or transient. Especially sinusoidal loads, such as sine sweep or stepped sine, are preferably used to investigate non-linear system behavior by analyzing the structure with varying load amplitudes. However, the use of a shaker requires a connection to the structure, which remains attached throughout the test. This makes shaker testing less flexible for in-the-field testing. In contrast, hammer testing provides the advantage of inducing the excitation force in a contactless way. As the hammer impact excites the structure over a wide frequency band, hammer testing is a very fast and convenient way to determine the compliance behavior of a machine tool. Since manipulation of the frequency content and amplitude of the compact is limited, it is less appropriate for analyzing non-linear system behavior. [6]

The second subsystem of the measurement chain provides the detection of the loads, which are induced into the machine tool structure. Therefore, piezoelectric crystals or strain gauges are used, which are integrated into the force flux between the machine tool structure and the exciter. The third subsystem consists of the measurement technique for detecting the vibration response of the machine tool structure. In addition to systems for direct measurement of the displacement, e.g. inductive transducers or optical measurement techniques piezoelectric accelerometers are used as well.

1.2.2.1 Frequency Response Function

The frequency response functions (FRF) represent the dynamic compliance behavior of a machine tool structure in frequency domain. Also, process stability and the occurrence of forced vibrations can be assessed on the basis of these measurement data.

For the determination of the frequency response function Fast-Fourier-Transformation-analyzers (FFT) are used. Therefore, the analog force and deflection/acceleration signals are sampled and digitalized. The sample rate determines the frequency range and the number of samples defines the frequency resolution of the analysis. To suppress high frequency disturbances analog force and deflection signals must be filtered before the digitalization.

The sampled time signals can be weighted by a so-called window function to avoid errors, which may occur when the signals are transformed into frequency domain. The type of window function depends on the signal that has to be analyzed. Commonly used functions are transient window (impact force), exponential window (response to an impact) and Hanning window. The transformation of the weighted signals into frequency domain is carried out by a discrete Fourier Transformation. The result of the transformation is a complex frequency spectrum, which can be depicted either as real part and imaginary part, magnitude and phase or as a Nyquist plot (Fig. 1.4). Separately from the depiction FRF describes the frequency-dependent deflection answer of a mechanical system regarding the dynamic load acting on it.

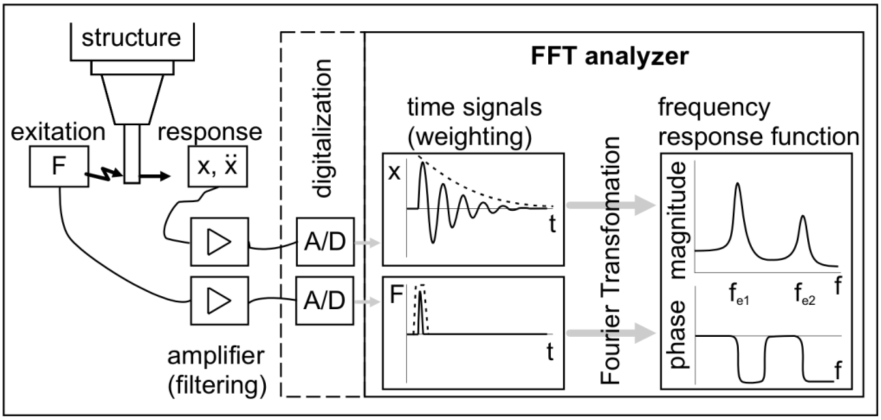

Fig. 1.4 Principle of the measurement of frequency response functions

1.2.2.2 Experimental Modal Analysis

Experimental modal analysis is a method for determining the dynamic characteristics of a structural system: its natural frequencies, mode shapes and damping factors. With these characteristics a mathematical model of the dynamic behavior of the system, a so called "modal model", can be formulated [5], [6]. The vibration of a linear time-invariant system can be described by a linear combination of its mode shapes, which are inherent to the dynamic system and determined by its physical properties (mass, stiffness and damping) and their spatial distributions. Coming from an analytical model, the system may be given in forms of partial differential equations and their solution provides the natural frequencies and mode shapes [7]. A more realistic physical model usually comprises mass, damping and stiffness matrices, which characterize the system properties. By solving the eigenvalue problem the modal data can be obtained. Utilizing finite element analysis almost every structure can be discretized into differential equations of motion and hence permits theoretical modal analysis.

Experimental modal analysis is a technique used to determine the modal model of a linear time-invariant system. By measuring the vibration response at one or more locations and the excitation force at the same or a different location and calculating their ratio several FRFs can be obtained. From these FRF-measurements a modal model of the mechanical system can be derived. In order to obtain an accurate

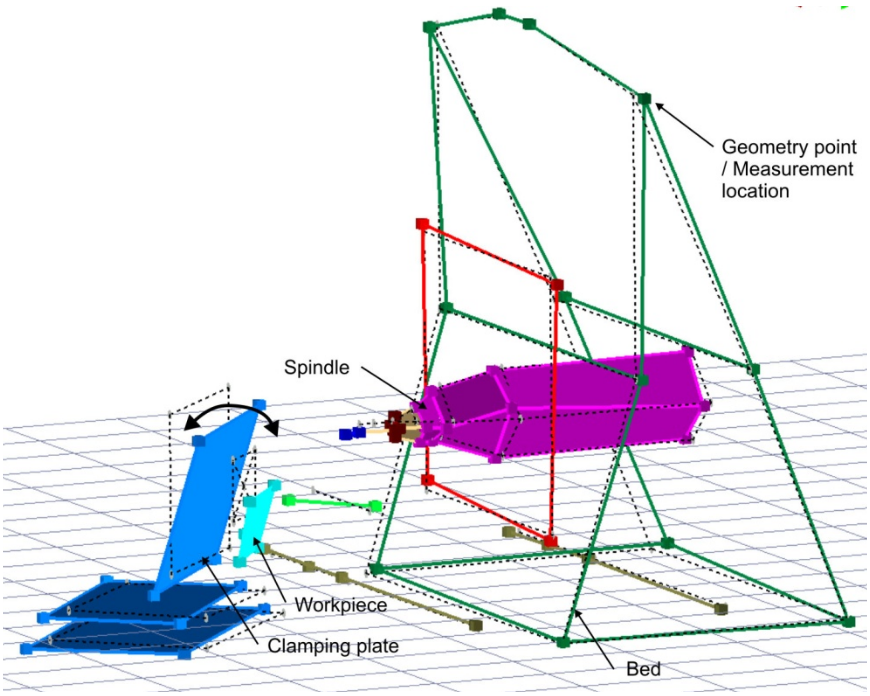

Fig. 1.5 Geometry model with measurement locations of a horizontal milling machine

modal model of the examined system the proper selection of excitation and response locations is of particular importance. The mathematical models obtained from modal analysis can also be used for the prediction of structure responses due to exciting forces or for substructure coupling when a simple dynamic representation is more suitable than a complex finite element model.

Figure 1.5 shows a geometric model of a horizontal milling machine. Each geometry point represents a measurement location in the machine tool. The structure was excited with an impulse hammer at several locations and the vibration response was measured using tri-axial acceleration sensors. The obtained modal model can be used, for example, to predict chatter vibrations or to identify structural instabilities.

1.2.3 Measurement of Kinematics

The accuracy of machine tools depends on a large variety of different influences. Geometric deviations in dimension of machined and formed workpieces can, according to [1], result in:

- Deviation of tool dimensions out of tolerances due to insufficient tool manufacturing
- Process-induced deviations such as tool wear or built-up edges
- Elastic deformation of the tool, the workpiece, clamping and support structures
- Deviations of the tool path regarding relative movement between tools and workpieces including force-induced deviations of the machine tool structure

Depending on the process the listed influences need to be considered when modeling the process machine interaction. A lot of different methods are available to measure the accuracy of the translational and rotational axes of machine tools. The spectrum reaches from simple measuring setups with test gauges, measuring straightness, parallelism, perpendicularity and concentricity up to complex and highly accurate methods. Some of these methods are described below.

1.2.3.1 Circularity Test

The circularity test allows the determination of the accuracy of a circular path, interpolated by a computer control unit. The deviations and vibrations can be traced back to the control unit, the drives and the machine kinematics. The test can be conducted using a double-ball-bar or a grid encoder. In the case of a grid encoder a photoelectric sensor moves over a plate, which contains a very precise measuring grid without contact. Using a double-ball-bar the circularity of the machine tool is determined by a position-measuring system. The system is integrated in the gauge. Performing the test with large radii gives information about the machine geometry, whereas small radii are used for the evaluation of the feed drive dynamics [1]. Afterwards, the measured path can be compared with the desired path. Figure 1.6 presents the measuring setup with a grid encoder (left) and a double-ball-bar (right).

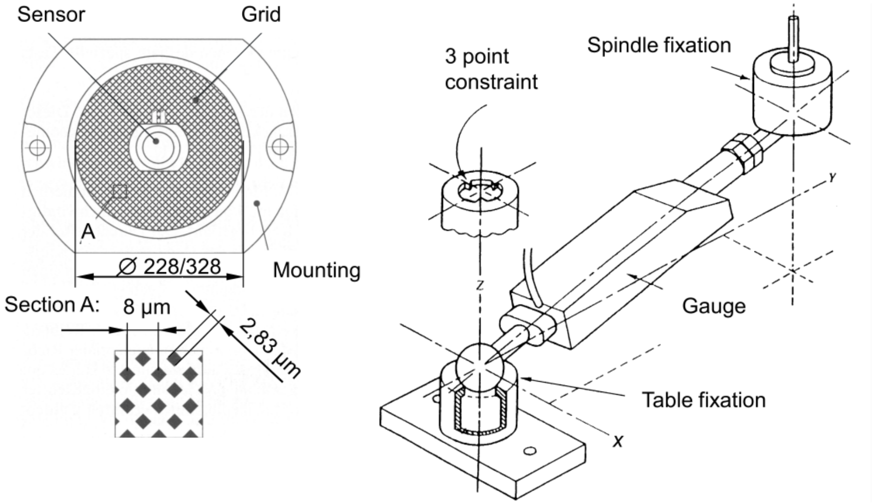

Fig. 1.6 Measuring setup for the ball-bar test with a grid encoder (left) and a double-ball-bar (right) [1]

1.2.3.2 Back-Step Test

During the back-step test several positions are approached from both sides. This is repeated for each axis. The current position is detected by an external measuring system at the tool-center-point (e. g. a grid encoder or a laser interferometer) and is compared with the desired position. According to the VDI/DGQ 3441 standard the parameters positional tolerance, positional deviation, reversal error, positioning scatter band and position uncertainty can be determined from the measurement data (see Fig. 1.7).

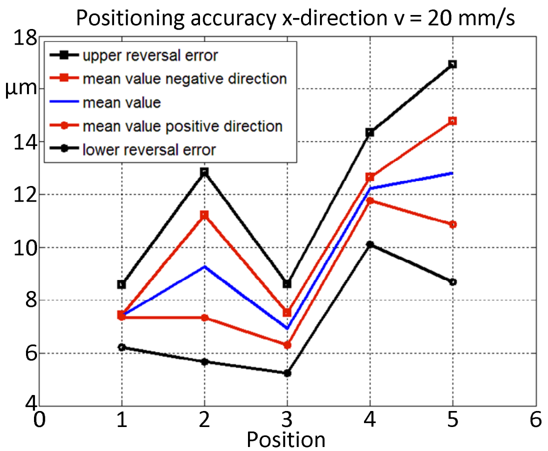

Fig. 1.7 Procedure of the back step method (left); characteristic diagram and determined parameters (right)

1.2.3.3 Measurement of the Machine Axes using Laser Interferometry

An approach for the determination of the kinematics of a machine tool is the measurement of the procedure movement of the machine axes. The measurement of the procedure axis is briefly described on the basis of a face grinding machine (Geibel & Hotz FS 635-Z CNC). The temporal response of the machine control was examined for the input of a correcting variable. The velocity and the acceleration of the machine table were measured. A laser interferometer system with a scanning rate of $f_a = 20$ Hz was used in order to avoid the influence of machine vibrations on the velocity and acceleration measurements. The change of movement between the interferometer and the retro reflector was measured with evaluation software. [8]

For the investigations the strokes were measured by several sequential starting points with constant, well-defined point distances at different workpiece velocities. The dependency of the workpiece velocity on the selected step size is shown in Figure 1.8.

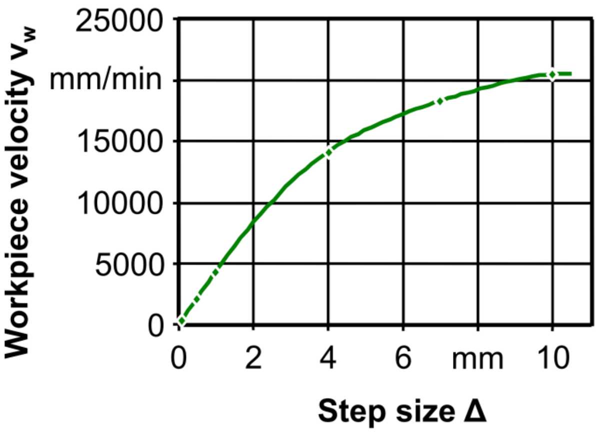

Fig. 1.8 Dependency of the workpiece velocity on the selected step size [8]

1.2.4 Thermal Machine Tool Behavior

Heat affects the static and dynamic properties of machine tools. The heat-related deformation on the machine components varies according to the material properties, the machine´s geometry and the conditions of the heat transfer. Consequently, the stiffness of the machine components is affected by the temperature. This has an impact on the production process and leads to dimensional deviations of the workpiece. The heat sources can be classified into internal and external sources according to where the heat is generated.

The internal heat sources include thermal dissipation losses, which have their origin in the limited electrical and mechanical efficiency of the machine components. The external heat sources result from heat transfer mechanisms such as conduction, convection or radiation caused by ambient heat flow. In addition, the process-induced energy losses due to the friction between the tool and the workpiece as well as the process heat have an impact on the temperature field of the machine [9]. Temperature measurements on machine tools and machining centers can be carried out according to the standards ISO 230-3 and ISO 10791-10 [10, 11]. The temperature distribution of the machine can be measured either at a finite number of individual points using thermocouples (contact measurement) or extensively via optical measurement systems (non-contact measurement via thermography camera / pyrometer) [12].

Especially the infrared thermography is applicable for this kind of measurement, for instance at press frames, because its surface has a homogenous radiance constant. Therefore, the emission factor of the radiating object, which can be determined by means of a reference measurement with an additional measuring system, has to be known. For the measurements of a finite number at individual points thermocouples or resistance thermometers can be used. These two types of temperature sensors differ in their measurement accuracy, cost, size, capability of measuring the surface temperature and vibration resistance (Tab. 1.1).

Table 1.1 Comparison of contact and non-contact measurement of temperature [12]

Contact measurement	Non-contact measurement
lower costs	no influence on measuring subject
more precise	local and extensive temperature measurement possible
easy to handle	

Thermocouples are available for different applications and then classified into different types. For example, thermocouples of the type T have an accuracy of ± 0.5 °C for a measurement range between approx. - 200 °C and 300 °C. Furthermore, this type is capable of measuring temperatures in fluids such as in the lubricating oil system [13]. In Figure 1.9, some types of temperature sensors are shown.

For measuring the temperature of the main eccentric shaft of a press electrically insulated thermocouples with screw threads are often applied as close as possible to the shaft. This can be done by fixing the sensor directly to the bearing of the eccentric shaft within the press frame or the connecting rod. For measurements which do not allow a screwing fixation of the thermocouples the sensors can be fixed with a thermal conductance paste and adhesive tape [9]. The signals of the thermocouples can be recorded with a PC including a measuring board. The measuring board should be equipped with an internal cold-junction compensation, which is required for thermocouples. Within this compensation the reference temperature is simulated by means of an integrated transistor. The difference in temperature between the junction and the measurement point induces an electrical voltage. For the measurement of the oil temperature in larger containers electrically-shielded resistance thermometers can be applied [13].

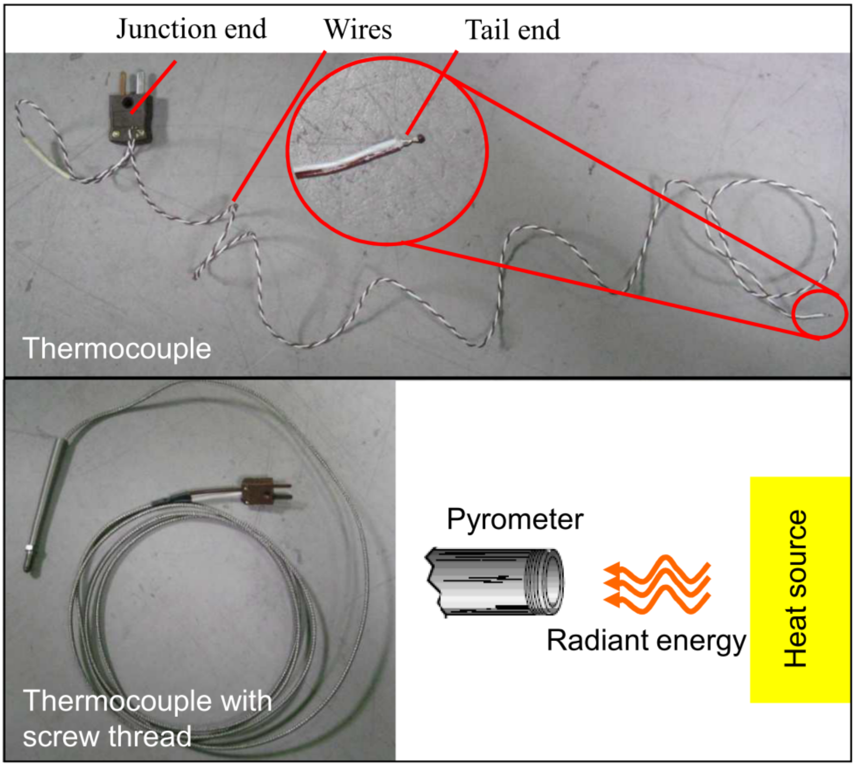

Fig. 1.9 Different types of temperature sensors for measuring the temperature of machine tool components

To consider thermal convection effects the temperature of the environment is defined as the reference. The characteristic temperature profile of a machine converges exponentially with time. The temperature at the components of the machine rises with high gradients during the starting phase of the machine in usage and converges gradually with further operating time towards a certain value. The temperature gradients and the end temperature are much higher for machine tools used for machining than for those used in metal forming. For the determination of a steady thermal condition of the machine the temperature increase of all relevant machine components has to be taken into account. Once a steady thermal condition is reached the production process of the workpiece is no longer influenced significantly by temperature effects. Figure 1.10 shows the different thermal conditions of a high speed stamping machine [9].

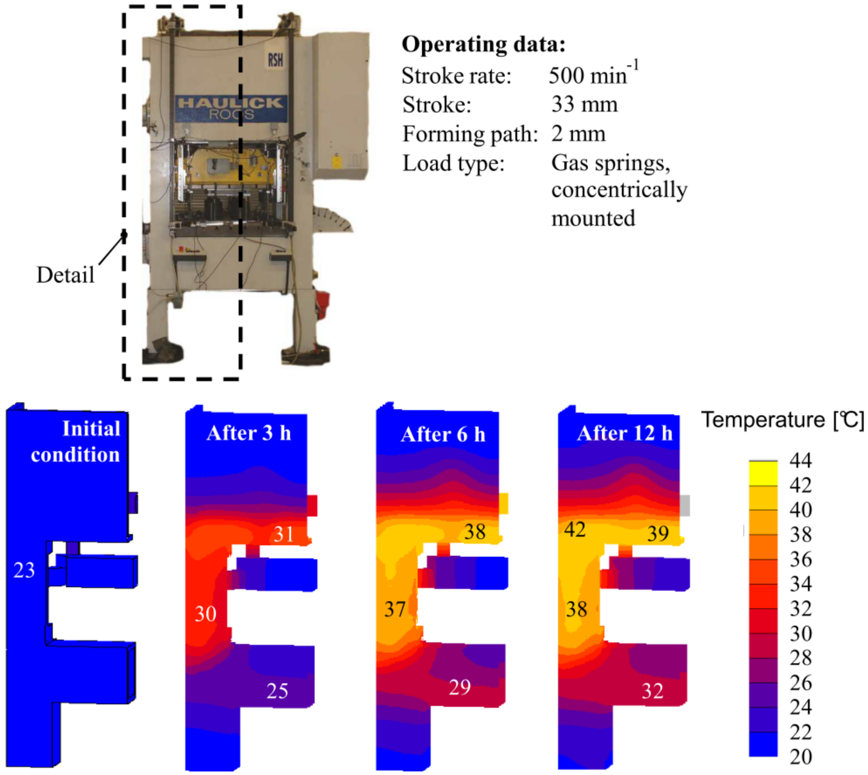

Fig. 1.10 Temperature profile of a high speed stamping machine [9]

1.3 Process Analysis

As depicted in section 1.2., precise knowledge about the machine tool structure is essential in order to achieve the best productivity and accuracy. Since the machine tool behavior interacts with the machining process, characteristics such as thermal, statical or dynamical loads have to be taken into consideration. Therefore, an experimental determination of process factors has to be carried out. The measured data such as process forces, temperatures, sound and vibration can be used for parameter identification and the evaluation of process models. In conjunction with the identified parameters of the machine tool behavior the boundary conditions for comprehensive process machine interaction (PMI) models can be defined.

In the following section, different measurement methods for the analysis of process forces (see Sect. 1.3.1) are described. Measurement methods and applications of acoustic emission (see Sect. 1.3.2) and temperatures (see Sect. 1.3.3) are given consecutively.

1.3.1 Process Force Measurements

Process forces are commonly used values for the characterization of manufacturing processes. Since there is a large variety of manufacturing processes where force measurements are of interest, the boundary conditions also differ. According to the different processes appropriate measuring devices have to be deployed considering the force magnitude and the process dynamics. For this purpose, the measurement procedure as well as the post-processing of the measured data may vary.

In this section, two commonly used measurement methods are described, which can be applied to cutting and forming processes. Subsequently, examples of force measurements covering a force bandwidth from a few tenths of newtons to several kilonewtons are given.

1.3.1.1 Force Transducer based on Strain Gauges

This kind of load cell consists of a steel body – the sensing device – which acts as a spring. On this body, strain gauges are applied as measuring devices. Thus, the forces are converted into elastic deformation. A calibration permits the correlation between the elastic strains and the applied force [14].

The basic effect of a strain gauge is the change of resistance in an electrical conductor due to the effect of mechanical stress, discovered by Wheatstone and Thomson [15]. This change of resistance in a single wire is very small. For that purpose, metal strain gauges with "wound wires", which form a kind of grid, have been developed. For an efficient production the grids are manufactured by etched foil technology nowadays. Apart from metal strain gauges there are other types of electrical resistive strain gauges, e. g. semi-conductor and vapor-deposited strain gauges [16].

Strain gauge-based force transducers can be used for static and dynamic measurements and are available in a variety of scales with nominal forces from about 10 N up to 5 MN. This range can be necessary, for example, for the measurement of forming forces in cold forging. However, with larger nominal loads the height of the transducers increases noticeably up to about 180 mm at 5 MN. Via a measuring amplifier and an analog digital converter the output signal can be recorded and processed electronically.

1.3.1.2 Force Measurement Based on Piezoelectric Elements

The piezoelectric effect is based on an interaction between electrical field strength, electrical displacement and the mechanical factors displacement and stress. If the piezoelectric element, e.g. quartz, is deformed mechanically, atoms in the crystal lattice are displaced. This leads to an outward charge displacement. Piezoelectric force transducers usually use the longitudinal effect in one direction. Long lasting quasi-static measurements require special attention to avoid drift of the output signal. A detailed description of piezoelectricity and measuring with piezoelectric sensors is given in [17].

Piezoelectric measurement devices, e.g. load washers and dynamometers, do not need a sensing device showing a considerable elastic deflection, which the