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Comparison of Rigid Body Mechanics and Finite Element Method for Machine Tool Evaluation

D. Kono¹, Th. Lorenzer², S. Weikert³, K. Wegener³

Abstract: Reconfigurable machine tools are proposed as manufacturing concepts coping with turbulent and quickly changing business environments. New tools for efficient modelling of different machine variants are required in order to facilitate and accelerate the reconfiguration of machine tools. This paper presents a software tool which allows the evaluation of the performance and conformance to requirements of machine structure variants at an early stage. In contrast to computer-aided manufacturing (CAM) tools which process numerical control (NC) code to predict the tool trajectory, this tool calculates the static and simulates the dynamic properties of the machine structure as a basis for machine evaluation. Models of different structure variants are assembled using a module library, which contains models of the available physical modules. Thus, different variants can be set up and analysed efficiently, significantly improving the data basis on which important and far-reaching decisions have to be made. An example illustrates how the tool can be used for obtaining information on the physical machine properties and how to interpret the results. The presented software tool is part of a methodology for the reconfiguration process of reconfigurable, modular machine tools.

Keywords: Machine Tool, Modelling, Rigid Body Mechanics, Finite Element Method (FEM)

1 Introduction

The manufacturing industry today has to cope with turbulent and quickly changing business environments, which have a growing impact on the manufacturing system requirements. Decreasing product lifetime and batch sizes result in forecasts of poor quality and reliability in terms of quantity and time horizon. When investing in expensive product-oriented manufacturing systems with limited adaptability, manufacturers face a considerable risk that these

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will not pay off. Furthermore, new manufacturing processes or materials might require adaptations or changes to the machines. Most of the currently used manufacturing machines are not capable of dealing with changing requirements with respect to capacity, functionality, technology or machine structure. If they are, then this is only in a very limited range and requires a lot of time and effort.

In response to the identified need for quick adaptation and change of manufacturing facilities, Koren et al. (1999) propose reconfigurable manufacturing systems (RMSs), which are designed with adjustable resources from the outset. Their major components at the machine level are reconfigurable machine tools (RMTs). Designed for specific operations at high throughput, they represent cost-efficient and effective manufacturing devices (Landers et al., 2001).

In recent years, machine tool manufacturers have come up with modular systems. However, these are only configurable at purchase but not reconfigurable at a later date. An exception are rotary axis add-ons for table and spindle heads; today already many machines can be equipped with these systems. Some prototypes of reconfigurable machine tools have been developed. Most of them are a result of research projects with the participation of industry partners who built the machines. Reconfigurability applies to them in terms of either technology or geometry or both (Wörn and Bauer, 2006). Despite some progress in developing modular, reconfigurable machines, there are still many unresolved issues. One of these is the lack of integrated simulation tools that provide support for machine tool builders and, notably, users at important stages of the reconfiguration (Wurst, Heisel and Kircher, 2006).

In this article, a software tool for the evaluation of the performance and conformance to requirements of machine structure variants at an early stage is presented. The calculation of the static and the simulation of the dynamic properties of the machine structure are the basis for a profound evaluation prior to far-reaching design decisions. For generating the machine models to analyse, a library of predefined module models, provided by their manufacturers, is used. In the existing literature, there is no similar software tool reported that is able to build machine model variants and predict the machine's static and dynamic behaviour efficiently each time.

2 Literature Review

Several connected issues, mainly in the sectors of RMT development and software for machine design and evaluation, need to be considered. The major challenges in the design of RMTs, of which the mechanical design process is a part, are explained by Pasek (2006). Design methodologies for RMTs that take into account the

geometry of the parts to be manufactured are presented by Moon and Kota (2002a, 2002b), Chen, Xi and Macwan (2005), Shabaka and ElMaraghy (2005) and Moon (2006).

Recent literature stresses the concept of autonomous mechatronic modules with maximum overlapping physical and functional system boundaries as components of RMTs (Heisel and Stehle, 2006; Kircher and Wurst 2006; Wurst, Heisel and Kircher, 2006). As these modules will not be optimised for their respective usage, Lorenzer, Kunz and Wegener (2007) propose to enhance the machine control by integrating an adequate model that reflects the physical configuration of the machine. The need for appropriate interfaces is expressed by Abele and Wörn (2004), while solutions for physical interfaces are presented by Gu and Slevinsky (2003) and Wörn and Bauer (2006); some research projects have even led to international standards, like the Desina project for electric, hydraulic and pneumatic installation technology in machine tools (ISO 23570-1; ISO 23570-2).

Altintas et al. (2005) developed methods and software tools for improving the design and evaluation of machine tool components and structures. Runde and Fisser (2004) and Neugebauer et al. (2005) discuss support from virtual reality techniques from the concept phase onwards. However, information about the physical behaviour of the visualised concepts is not available. Vichare et al. (2007) present a methodology for building functional models of machine tools which take into account the machine kinematics but not the physical properties of their components. Brecher, Weck and Müller-Held (2005) developed a visualisation environment for the results of finite element (FE) analyses as well as the evaluation of machine kinematics. For some components, models have been built up to demonstrate the optimisation of their properties, e.g. for a machining centre headstock (Jedrzejewski et al., 2004), machine tool spindles (Altintas and Cao, 2005) or a ball screw feed drive system (Zaeh and Oertli, 2004); all of these models are based on the finite element method (FEM). Bianchi et al. (1996) derived a structural machine model from the FE model in order to evaluate the dynamic behaviour of the machine. For generating mechatronic models that can be used in different simulations, Zaeh and Baudisch (2003) presented an environment which integrates the various aspects of mechatronic systems. The above-mentioned methods need quite detailed information, which is not available as long as the machine structure is not determined. Yigit and Ulsoy (2002) evaluate the dynamic stiffness of RMT variants but they do not obtain information on the tool centre point (TCP).

In contrast to these systems, the presented tools for generating machine structure variants, which are based on the selection of appropriate machining modules for given manufacturing tasks, cannot provide physical information on the obtained structure variants (Heisel and Meitzner, 2002; Kircher, Seyfarth and Wurst, 2004). Considering the state

of the art in simulation of machine tools, there remains a clear necessity for suitable tools for the efficient prediction of the static and dynamic behaviour of RMTs, entirely or partly made of ready-to-use modules.

3 Design Procedure for Reconfigurable Machine Tools

RMTs have to be designed for the purpose of being reconfigured by the machine user. This implies that planning a reconfigured machine and executing the reconfiguration must be feasible with the knowledge and experience of production engineers and machine operators. In addition, an economically advantageous reconfiguration must be performed with moderate means. Expensive tools, specialised staff or other costly devices should not be necessary for a reconfiguration, otherwise RMTs will not be accepted by machine tool users.

For conceiving and evaluating possible machine structures, users and manufacturers can work with the same tools. Nevertheless, machine or module manufacturers need additional functionalities for generating the virtual models which are delivered with the corresponding physical modules. These physical and virtual module libraries facilitate and accelerate the repeated reconfiguration of machine tools in compliance with requirements.

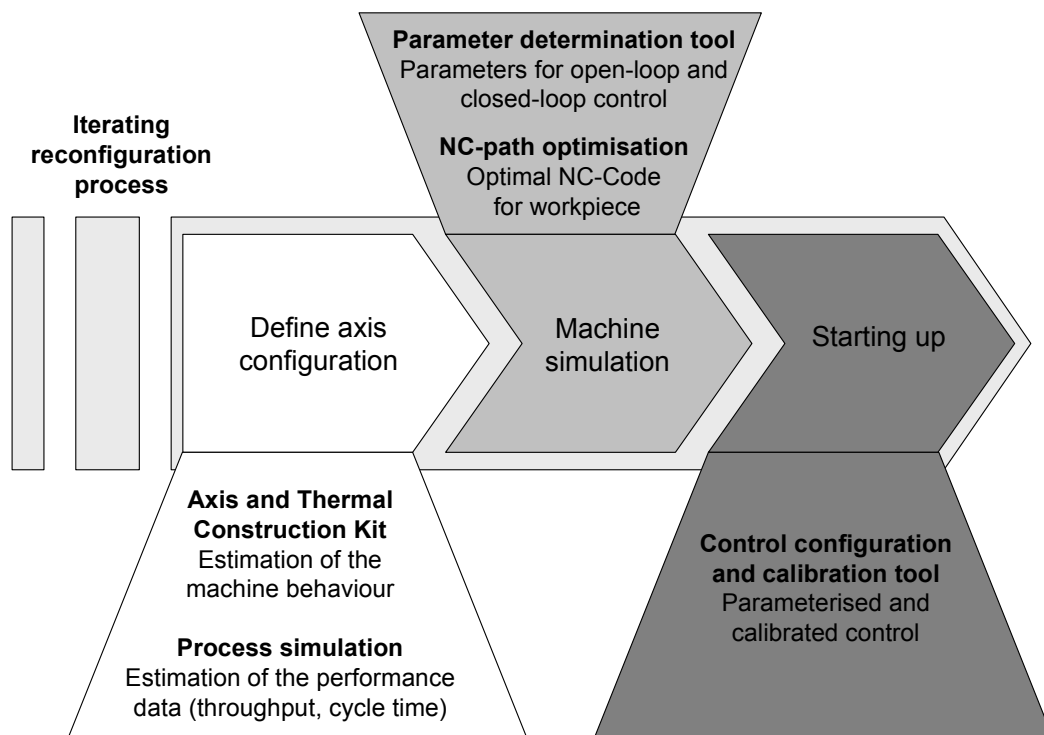


Figure 1. Necessary software tool support for machine tool users during the reconfiguration process.

Figure 1 shows the three major phases of the iterating (re)configuration process. The next sections briefly describe each phase before going into detail about the evaluation tool as the main element of the first phase. In every phase, different tools are needed to accomplish the current task best. However, all tools access a virtual machine model which evolves during this process. Hence, consistency of the machine model is a crucial factor.

3.1 Definition of the Axis Configuration

A virtual module library contains models of all available physical modules. As a first step, the configuration of the machine tool's axes and spindles is chosen. Thus, a virtual model of the entire machine can be generated, providing all necessary data for preliminary calculation or simulation, respectively. The configuration can be tested on static and dynamic behaviour in order to obtain reliable information for decisions concerning the machine structure.

Good performance across the working range is a crucial criterion for the quality of the reconfigured machine structure. In the case of RMTs, good performance means above all low displacements and high eigenfrequencies at a given velocity, acceleration and other boundary conditions (manufacturing task, available modules), which determine considerably the machine configuration. Quasistatic evaluation techniques can be used in order to accelerate the performance assessment at varying positions in the workspace. When the criteria to optimise are known, the machine tool user is able to evaluate different machine variants with respect to fulfilment of the requirements.

Additionally, process simulation including material removal could be used to obtain further performance data. Similar to existing CAM systems, the throughput or cycle times could be estimated for given drive properties, operation tasks, tool path and machining parameters. Performance tests for different products or slightly changed conditions are conceivable, too. This would allow estimations of the short-term flexibility of the considered variants without reconfiguration. The additionally obtained data on the manufacturing capacity would make further decisions even more well founded.

A reliable analysis of these preliminary estimations leads to more objective and certain decisions on the variants to keep than without this information. Hence, the number of chosen variants for further consideration should be manageable, so that more precise analyses without excessive deployment of resources are possible and reasonable.

3.2 Machine Simulation

In the next step, the necessary data for the commissioning of the reconfigured machine has to be determined. The initial input data for generating the simulation models has to be provided by the module manufacturers. They have the means to describe their modules very precisely, using *e.g.* FE simulations or experiments.

The uncomplicated configuration and calibration of the control is of particular importance. Once the machine model has been set up, the control parameters have to be determined. Structure-independent parameters will be given in the module models. Others must be deduced from the provided data and the results of the machine simulation. The control parameters and supplementary information for its configuration are written into a control configuration file.

Single aspects may require specific simulations based on data of the provided module models, as Bamberg (2000) demonstrated for eliminating variants at early stages. This applies especially when dealing with complicated structures or unusual module combinations. In order to ensure the quick and correct reconfiguration of the physical machine, *i.e.* the assembly on the shop floor, it has to be prepared as much as possible in advance.

The machine models at this stage are sufficiently detailed to run a path optimisation for the numerical control (NC) (Zaeh and Baudisch, 2003) before setting up the real machine. Thus, one can detect collisions between workpiece and tool, determine the program duration and obtain more information on the expected accuracy of the TCP trajectory. Correct and efficient NC code contributes considerably to short ramp-up time, one of the strengths of RMTs. However, time-based simulations can only provide good results if the available input data is sufficiently accurate. Substantiated evaluations and reliable comparisons require that the models are equivalent in terms of their level of detail. Otherwise, there is a serious risk of errors in comparing and interpreting the obtained information.

3.3 Commissioning of the (Re)configured Machine

In the final phase of the reconfiguration process, the machine control is configured. As this procedure will recur various times during an RMT's life cycle, the support of an adequate software tool is crucial for efficient commissioning.

Every modification of the machine structure requires adjustment of the control parameters to the current machine configuration. For that purpose, the parameter estimates obtained during the second step can be transmitted to the control as a whole set of initial values. Geometrical constraints, like the workspace boundaries, can be adopted as they are. Others, like the gains, will need separate adjustment and accurate calibration. For this procedure, the support of a control configuration and calibration tool is necessary, which is able to deal with most common controls.

The presented methodology is applicable for the development of RMTs consisting of stand-alone modules and possibly required further connection elements. Such modules are explicitly designed for this purpose, and the manufacturer must provide all necessary data for their efficient use. Figure 2 shows the reconfiguration process for such a machine tool. After the formerly described assembly of the virtual model and the generation of the software, the real machine is assembled on the shop floor using the corresponding modules from the physical library.

In the following, a software tool for the first phase of the reconfiguration process is presented. The Axis Construction Kit is proposed as a source of extended information based on calculation and simulation. It aims at supporting engineers in decisions on eliminating variants. Only a few promising variants should be kept and all effort should be made to optimise them.

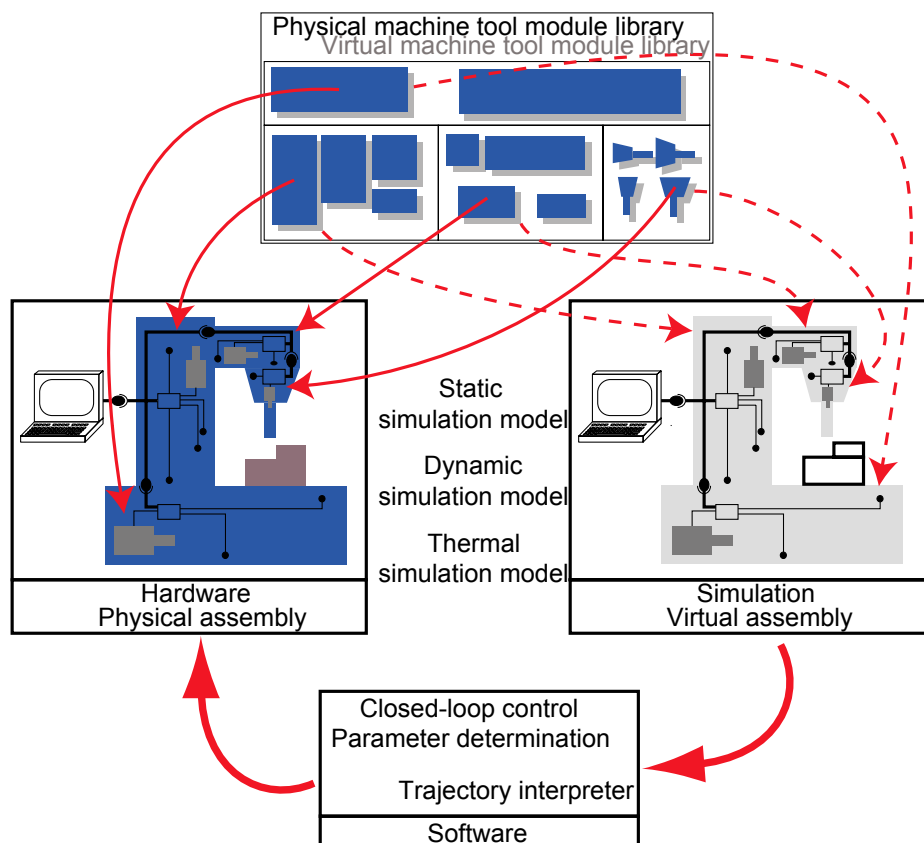


Figure 2. Reconfiguration process for a machine tool: modelling of the machine using virtual modules (right); generating necessary software (below); assembly of physical machine (left) using modules from the library (above).

4 The Axis Construction Kit as a Modelling and Evaluation Tool

Decisions on the structure of a machine have to be made very early in the design process. As the structure's impact on machine performance and accuracy is considerable, determining a functionally good and robust structure is crucial for the quality of the machine tool. This issue is particularly important for RMTs that are assembled from ready-to-use modules which obviously cannot be optimised individually for every possible configuration. At this early stage, there are generally only a few data available upon which these decisions can rely.

The Axis Construction Kit enables machine tool users to obtain reliable information on the future machine behaviour of different machine configurations in a very short time. These configuration variants are preferably generated using the available models in the module library. By this means, several structure variants of machine tools can be modelled and evaluated efficiently. With this additional information, some uncertainties are eliminated, which leads to well-founded decisions. The library is expandable so the machine tool user has the possibility to add module models to his database. Thus, at every reconfiguration, he has at his disposal all relevant models.

The Axis Construction Kit, especially designed for modelling machine tools, was developed at the IWF and has served in various analyses of conventional machine tools (Weikert, 2000). Major advantages, besides the effectiveness in terms of mathematical operations, are the modularity, adaptability and flexibility of the software. For the further development of the Axis Construction Kit, which is an important issue in our research projects, the cited properties represent significant conveniences. In contrast to commercial CAM tools, the Axis Construction Kit takes into account the physical properties of the machine components and not only the geometrical attributes.

4.1 Functions

The Axis Construction Kit consists of several functions which are performed consecutively during the modelling process. After starting the **Axis Construction Kit** window, the user first selects the spindle alignment to determine the machine coordinate system. Next, the user has the choice between several predefined machine configurations and an empty model. The predefined machine models cover the most common milling machine types with vertical or horizontal spindles. The empty model can be used when modelling a completely different machine type or kinematic structure. Immediate visualisation of the machine during every step helps to avoid geometrical input errors.

In the **Machine Definition** menu (Figure 3), the machine structure is assembled. Machine components like tables, beams or predefined modules can be added, positioned and, where applicable, sized. The components are

represented as primitive bodies like cuboids, prisms and cylinders. Properties like mass, moment of inertia etc. can be set if they are known from other sources. Otherwise, they are calculated for the respective primitive body, taking into account the typical design parameters of the represented machine components. Available module models can be included in the module library from which the desired modules are chosen for assembling the virtual machine. These models are fully described and contain all property data for each component of the module.

Such a library usually contains several modules that differ in dimension, weight, stiffness or other key characteristics, *e.g.* a direct or indirect position feedback system. RMTs should consist mainly of these modules as this facilitates the reconfiguration for the user. The assembly direction of modules and bodies is determined immediately at selection. Any necessary transformations of modules, which are modelled in their own coordinate system, are performed at the integration of the respective module. After having added all the machine components, the user defines the kinematic chain according to the Schwerd convention and assigns the reference bodies for tool and workpiece by entering the index of the corresponding body. The workspace boundaries determine the accessible space for the calculations specified in the Output menu and are given by the user. However, it would be possible to deduce the maximum theoretic workspace from the kinematic machine model and the moving range of each module.

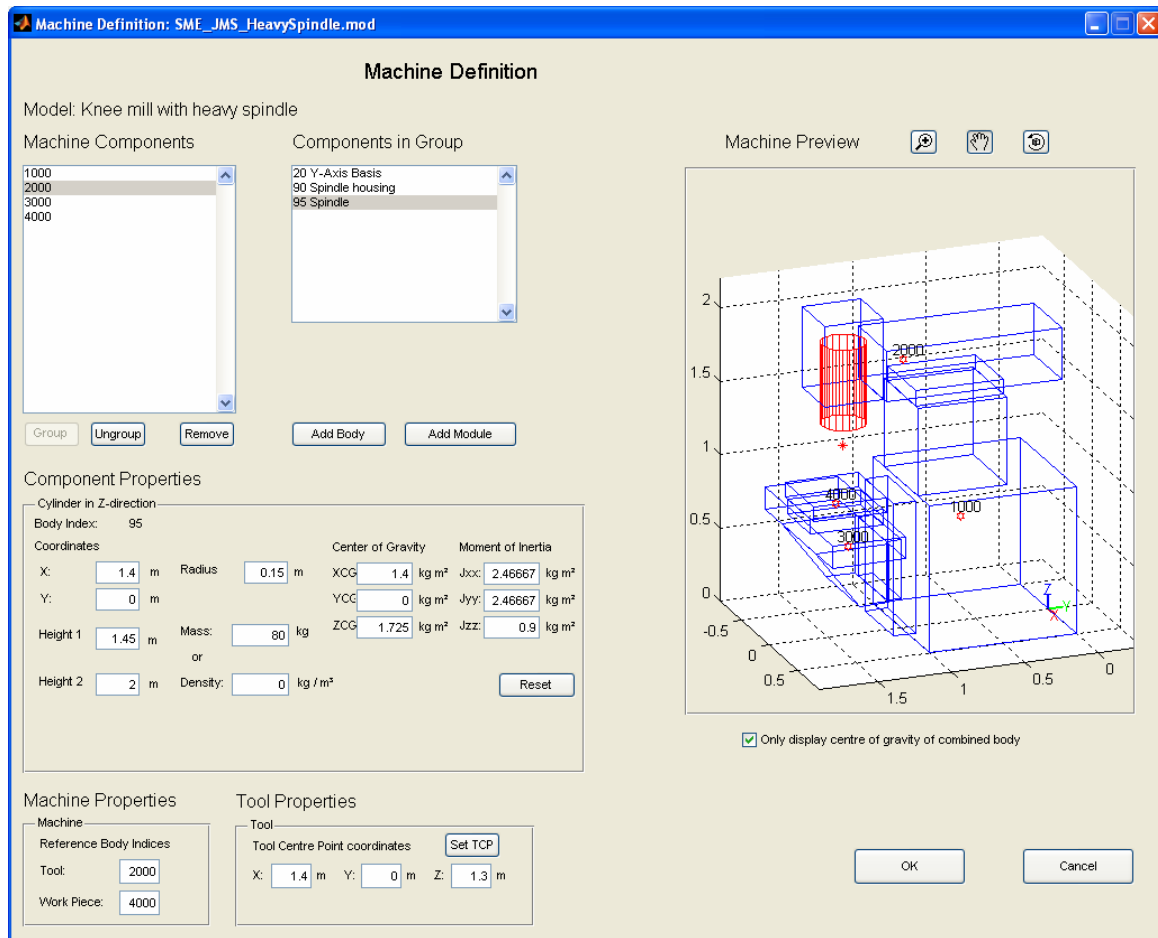


Figure 3. Definition of the machine configuration for the Axis Construction Kit.

The **Drive Definition** menu is used for defining the moving axes's drives and position feedback systems and for setting their respective properties: drive type, reference bodies for drive and position feedback system, and the exact location of the measuring heads. Significant drive properties, like its inertia, the stiffness of the coupling to the shaft and the point of the load incidence, complete the input data for the model. For each drive type, the necessary information is queried, so that the impact of the defined drives on the system can be considered immediately. At this early stage, programmable logic control (PLC) features are not considered and therefore remain omitted.

In a similar manner, the couplings between the different components, modules and the base are defined in the **Coupling Definition** menu. Various types of couplings can be chosen, *e.g.* a set of distributed one degree of freedom (DOF) stiffnesses orthogonal to the direction of movement for a linear guideway or 3D stiffnesses for the basement fixation. All couplings may be arranged in a way that corresponds best with their functional role. Physical damping

values can be chosen individually. After setting all necessary couplings, the system matrices (mass, stiffness, damping) of the machine model can be generated for the calculation of the static displacements of the TCP.

The positions at which the displacement shall be evaluated as well as the information and figures to be displayed are set in the **Output Definition** menu. The user chooses one case out of a list of predefined evaluation patterns. Due to visibility, for linear, two-dimensional and three-dimensional arrangements of measuring points, only the static properties are evaluated, whereas for single points the dynamic properties can be calculated, too.

The calculation of the machine properties is started by pushing the **Calculation** button. Thus, the user obtains as static properties the displacements at the TCP under quasistatic loads such as gravity, process forces and moments, or inertia forces due to acceleration of axes. At distributed measurement points, the sorted eigenfrequencies can be visualised as well. For a single measurement point, the static properties are shown explicitly, while the dynamic compliances are visualised over a predefined frequency range. In order to support the understanding of the structural behaviour, the deformed structure and mode shapes can be chosen as output for a single “measurement point”.

The **Simulation** menu leads to the evaluation of the machine behaviour in the time domain. It provides the displacements of the TCP while running a user-definable test trajectory with given parameters (*e.g.* positioning length, velocity, acceleration, jerk). To simplify the interpretation, the results are displayed as figures which show the actual TCP path in the three coordinate planes and as a time series.

The possibility of including ready-to-use module models in a library significantly reduces the modelling time compared to conventional modelling of each component. It is a necessary feature for software that is meant for supporting the users of RMTs in reconfiguring their machines on their own. As the properties and parameters of the used modules are determined by the module manufacturer, the user should rely on quite accurate data. This improves the quality and reliability of the obtained results and therefore of every subsequent decision based on them.

4.2 Content and Structure of Module Models

The use of modules from a library requires that they are modelled in a format which provides all the necessary information for assembly in a machine. Besides the actual data on each component, information is needed on some properties of the module as a whole and the proper use of it. An exemplary summary of the data that should be given in a module description file is shown in Table 1. Based on these requirements, a model format has been developed for use with the Axis Construction Kit.

Table 1. Summary of a module description, containing important data for generating the complete machine model.

	Description	Unit
Bodies		
Dimensions	Length, width, height	[m]
Moving range	Travel limits, length	[m]
Mass	m_n	[kg]
Density	ρ	[kg/m ³]
Centre of gravity	X, Y, Z position	[m]
Moments of inertia	$I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{xz}, I_{yz}$	[kg m ²]
...		
Drives		
Type	Ball screw drive, direct drive, pinion gear drive, belt drive	[-]
Point of load incidence	X, Y, Z position	[m]
Position of measuring system	X, Y, Z position	[m]
Reference body	Reference body for measuring head and scale	[-]
Drive power	P_D	[kW]
rpm	Nominal, maximum	[1/min]
Maximum speed	Maximum traverse velocity	[m/s]
Maximum acceleration	a_{max}	[m/s ²]
Drive stiffness constant	k_d	[N/μm]
...		
Interfaces		
Flange dimension	X, Y, Z position	[m]
Coupling stiffness	k_f	[N/μm]
...		
Thermal properties		
Linear expansion	α of body material	[1/K]
Thermal conductivity	λ	[W/m K]
Specific heat capacity	c_p	[J/kg K]
Young's modulus	Young's modulus of body material	[GPa]
Poisson's ratio	ν	[-]
...		
Further components		
Temperature sensor	Range of values	[K]
...		

Each module model consists of the specific models of its components and the data concerning the whole unit. Basically, the components are modelled as primitive bodies like any other body that can be selected in the Machine Definition menu. Each component is defined by a certain set of values (index, mass, centre of gravity, etc.), which is the same for all available body types. The underlying mechanical equations need the component's mass or density, shape and dimension as minimum input data, which already provides good results. More detailed component information, *e.g.* the exact centre of gravity or moments of inertia for the real body shape, improves the accuracy of the results. A matrix whose lines correspond to one set of values each then contains all module components. Geometry information for the components is given in the module coordinate system. Hence, when using such a module in a machine model, a coordinate transformation has to be applied to all bodies in order to obtain the correct representation of the module in the machine coordinate system. Drives and couplings of the module are defined in a similar manner and the corresponding values are stored in separate matrices. In both cases, the minimum data are type, exact location and coupling stiffness. Due to the fact that collision detection is out of scope, the coarse geometric representation used in the Axis Construction Kit is sufficient.

The mentioned data is part of the actual module file in which all the information is collected, like a container. Besides the component data, there is meta-information with which the machine model file must be furnished. The indices of the module's components are stored in a description variable. Together with the information about possibly combined bodies, *i.e.* solids consisting of more than one primitive body, and the kinematic chain matrix, the structure of the module is entirely defined.

To avoid improper assembly of the modules, supplementary information about their alignment and the connectivity of the flanges must be available. Each module is equipped with predefined dummy couplings that are located at the flange components of the module. The stiffness of the resulting couplings at a connection between modules or flange components will be initialised with a default value for mechanical connection elements, *e.g.* bolts. The connection direction of each flange is assigned so that it cannot be used the other way round. This is important for directional modules like stacked two-axis modules with a second axis drive less powerful than that of the basis axis. The connecting direction of a flange is indicated by -1 or +1, respectively, and stored separately as a description of the dummy coupling; flanges can only be connected when their connecting directions neutralise each other. Then ordinary couplings are generated at the position of the dummy couplings and are added to the model, thus connecting

the two involved flanges. Supplementary information about stacking possibilities and preferred orders can be used to prevent invalid axis combinations.

When adding a module to a machine model, the content of the module description file is duplicated so that only a copy of the original data is used and modified in a specific machine model (Figure 4). The user specifies an index number for the new module, which will be the basis number for all components of the module.

Before applying the newly generated indices to the components of the inserted module, all existing body indices in the machine model have to be checked on coincidence with these. If there is any overlapping, the user is forced to choose a different base index. The same procedure has to be applied for the drives' indices.

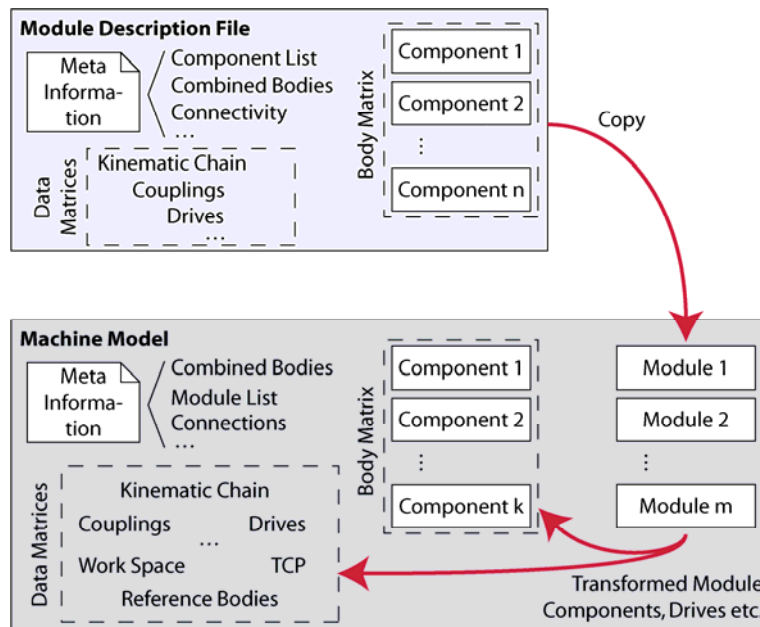


Figure 4. Content of module description file and machine model for the Axis Construction Kit. A machine model is built by combining copies of the module description files and supplementary information on other components.

When the assembly location is selected, the necessary coordinate transformation can be performed. The applicable transformation matrix is determined by comparison of the module coordinate system with the axis direction and origin at the corresponding flange. Internally, it has to be applied to every single module component as well as on the kinematic chain matrix; however, the user only perceives the transformation on the module as a whole.

In order to prevent unintentional changes to single components of a module, it has to be marked as an invariable unit. To ensure this, the machine model manages a list of all modules and their components. Requests referring to a component of such a listed module are transmitted to the module. Obviously, there are only a few operations allowed on modules, such as translation or rotation, respecting the constraints set by the flanges.

The above-described elements of the model format contain the information that is needed in the first phase of the reconfiguration process for modelling the machine structure with the Axis Construction Kit. Of course, supplementary data, as listed in Table 1, should be stored in the model as well, so that it is available in later phases.

4.3 Significance of Retrieved Information

The calculation and simulation provide the necessary information for evaluating a new machine configuration. The static and dynamic properties of the machine structure are calculated using methods described by Weikert (2000) and Zirn and Weikert (2006), thus providing the user with physical information on the machine behaviour. The Axis Construction Kit calculates the displacement of the TCP in the workpiece coordinate system under given loads for a chosen set of points. In general, one would try to cover the workspace by choosing the extremal values, which gives an idea of the variance range, and the centre point of the workspace.

At the same step, the frequency properties of the structure are calculated. This allows comparison of eigenfrequencies and mode shapes of the different structure variants. With knowledge of these values, an experienced designer gains a clear idea of the expected capacity of the considered machine, especially in comparison to other variants. Less experienced users, however, will need further assistance, which would be best integrated into the program. The simulation of the tool moving along a representative path allows tracking of the displacements of the TCP in all three dimensions at the same time. Significant systematic path deviation due to dynamic loads can be detected very early and subsequently can be reduced by conceptual modifications.

It has to be added that assessment of machine tool concepts using simulated TCP trajectories has to be done with caution. As the certainty of the obtained absolute values depends, as in most simulations, on numerous parameters which often cannot be determined accurately enough, it should mainly be applied for comparisons. In order to reduce the number of parameters to adjust, the control and drive models in these simulations are kept on a quite basic level.

All this physical information is obtainable within a very short time at an early stage of the machine design. The actual calculations and simulations take only seconds. The duration of the modelling of the machine depends on the level of detail of the provided module models and on the complexity of the machine configuration. The main advantage and benefit is the efficient way to obtain data which provides decision-makers with reliable information for well-founded decisions on the choice of the machine configuration and its basic conceptual parameters, resulting in significantly better, *i.e.* suited for the given tasks, machine structures. The impact of the machine configuration on the machine behaviour is crucial, however; once determined, structural changes are very complicated and expensive.

5 Example

When reconfiguring an RMT for a specific task, one has a choice of several available modules, *e.g.* light and heavy modules, linear axes with small and large distances between the guideways or machining unit assemblies resulting in multiple tool configurations. In order to make the right choice, the impact of a certain configuration on the resulting static and dynamic properties needs to be evaluated and compared. The efficient use of the Axis Construction Kit for setting up and analysing machine variants is demonstrated by the following example case.

We consider the configuration of a knee-mill machine which is designed to be equipped with diverse spindle units. We assume that the given machining task can be accomplished in several ways, each using a different set of operations on various machine tools and requiring certain spindle properties on each of these. However, the underlying workpiece requires that the given workspace dimensions remain respected. In this case, we examine three spindle units which are supposed to be able to deal with the requirements of one operation set on one RMT: one heavy unit with a powerful spindle for rough machining, one light unit with a high-speed spindle for finishing and one light unit with an additional rotary axis. Table 2 shows the key characteristics of and the main differences between these resulting machine variants.

Table 2. Main parameters of the resulting knee-mill machine variants.

	“Heavy version”	“Light version”	“Light version with rotary head”
Spindle mass	80 kg	30 kg	30 kg
Mass of spindle housing	110 kg	35 kg	35 kg
Mass of rotary axis	-	-	25 kg
Location of centre of gravity of spindle unit	X: 0 m Y: 1.40 m Z: 1.84 m	X: 0 m Y: 1.35 m Z: 1.74 m	X: 0 m Y: 1.35 m Z: 1.73 m
Kinematic chain	Y-[T, WP]-X'-Z'	Y-[T, WP]-X'-Z'	Y-B-[T, WP]-X'-Z'
Workspace	500×400×400 mm ³		

5.1 Quasistatic Evaluation

The three variants for the quasistatic evaluation can be generated quite easily and quickly with the Axis Construction Kit, compared to other modelling tools. The modelling time for the first machine variant is less than 45 minutes, provided that the data of all components is at hand. As the three variants only differ at the spindle level, the necessary modifications to obtain the remaining two models can be implemented in about 10 minutes each. The mass of the heavy spindle unit is significantly higher than the masses of the two light spindle units. In addition, the

location of the centre of gravity of the respective spindle units differs in each configuration. The impact of these differences needs to be analysed before a decision on which variant to build is taken. The evaluation is conducted with regard to the criteria cross-talk effects (*e.g.* vertical displacement when accelerating in the Y direction) (Weikert et al., 2007), frequency-dependent (dynamic) displacements of the TCP in the workpiece coordinate system due to process loads, and eigenfrequencies and their corresponding modes.

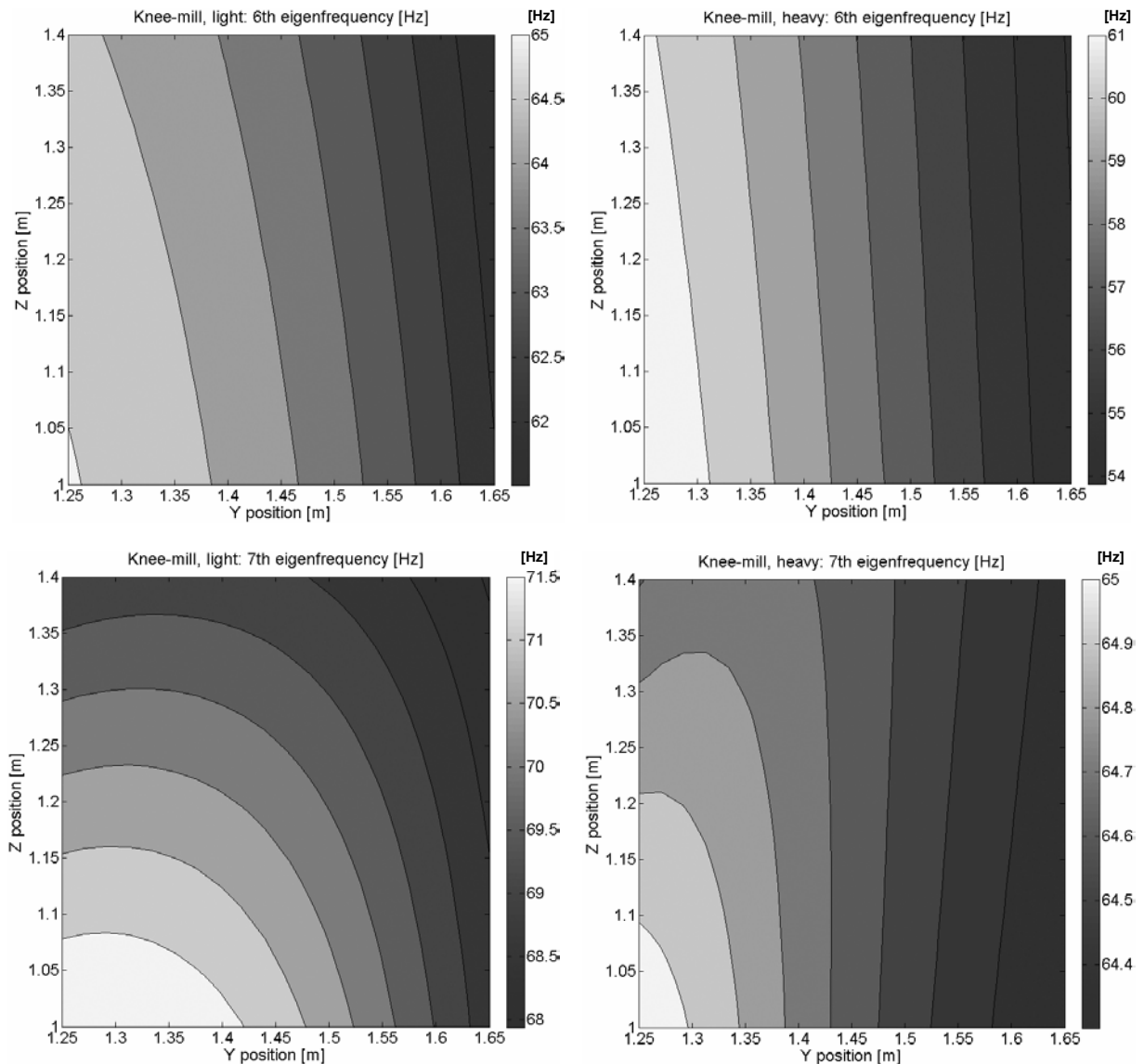


Figure 5. Distribution of 6th (above) and 7th (below) eigenfrequency for light (left) and heavy (right) spindle unit variants.

Figure 5 shows the distribution of the values of the sixth and the seventh eigenfrequency over a vertical plane through the centre of the workspace for the light and the heavy spindle unit variants. The higher eigenfrequencies of

the light spindle variant are a result of the smaller mass of the spindle unit. For this reason, the eigenfrequencies of the light rotary variant and their distributions are similar to those of the light spindle variant. While the eigenfrequencies 1 to 4 and 11 remain rather unchanged due to the alterations in the configuration, the eigenfrequencies 5 to 10 and 12 are clearly affected.

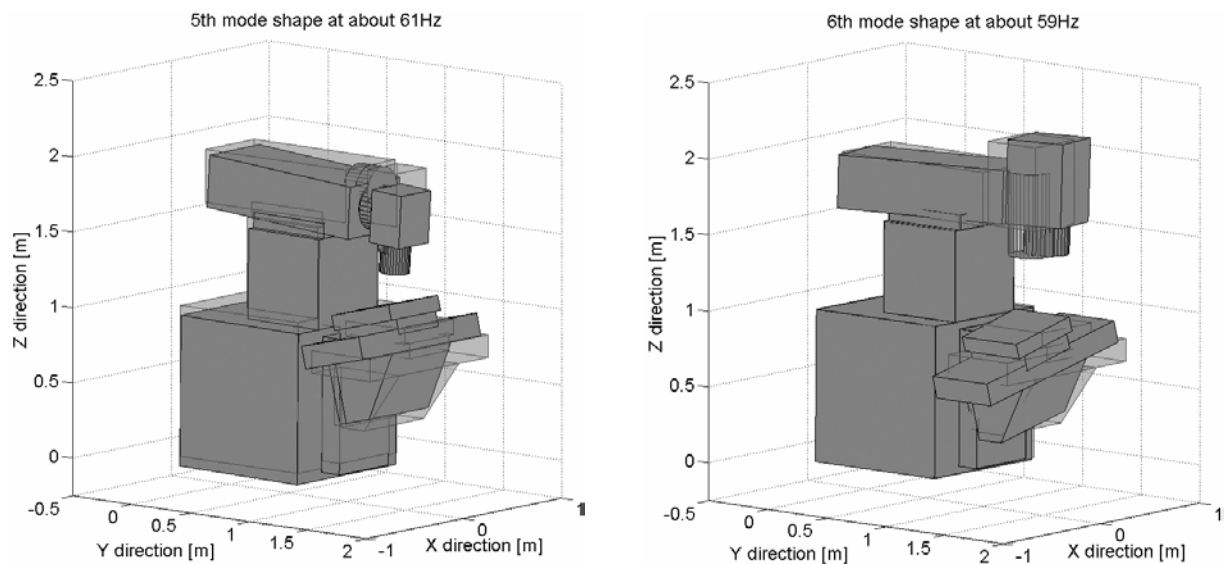


Figure 6. Mode shapes of the 5th (left) and 6th (right) mode, visualised for the light rotary (l) and heavy spindle unit (r).

In Figure 6, the modes 5 and 6 are visualised for the light spindle unit with rotary head and the heavy spindle variant, respectively. The light grey drawings indicate the initial position of the machine and the dark grey drawings show one extremal position. When evaluating different modes, the corresponding mode shapes lead to an effect between tool and workpiece which generally results in undesired, visible marks or patterns on the workpiece surface. The frequency-dependent dynamic compliances due to process forces between tool and workpiece for the three variants are shown in Figure 7. In these graphs, the compliances in the X, Y and Z directions are shown for process forces being applied in the x, y and z directions accordingly. As a result of the changing configuration, the peaks at 57 and 59 Hz for the heavy spindle variant correspond to the 5th and 6th mode shape move to 61 and 64 Hz for the light spindle variants. The additional peak in H_{yy} at about 68 Hz for the light spindle with rotary head is due to supplementary mass of the B axis drive combined with the reduced stiffness at the connection of the spindle head to the Y axis via the rotary drive.

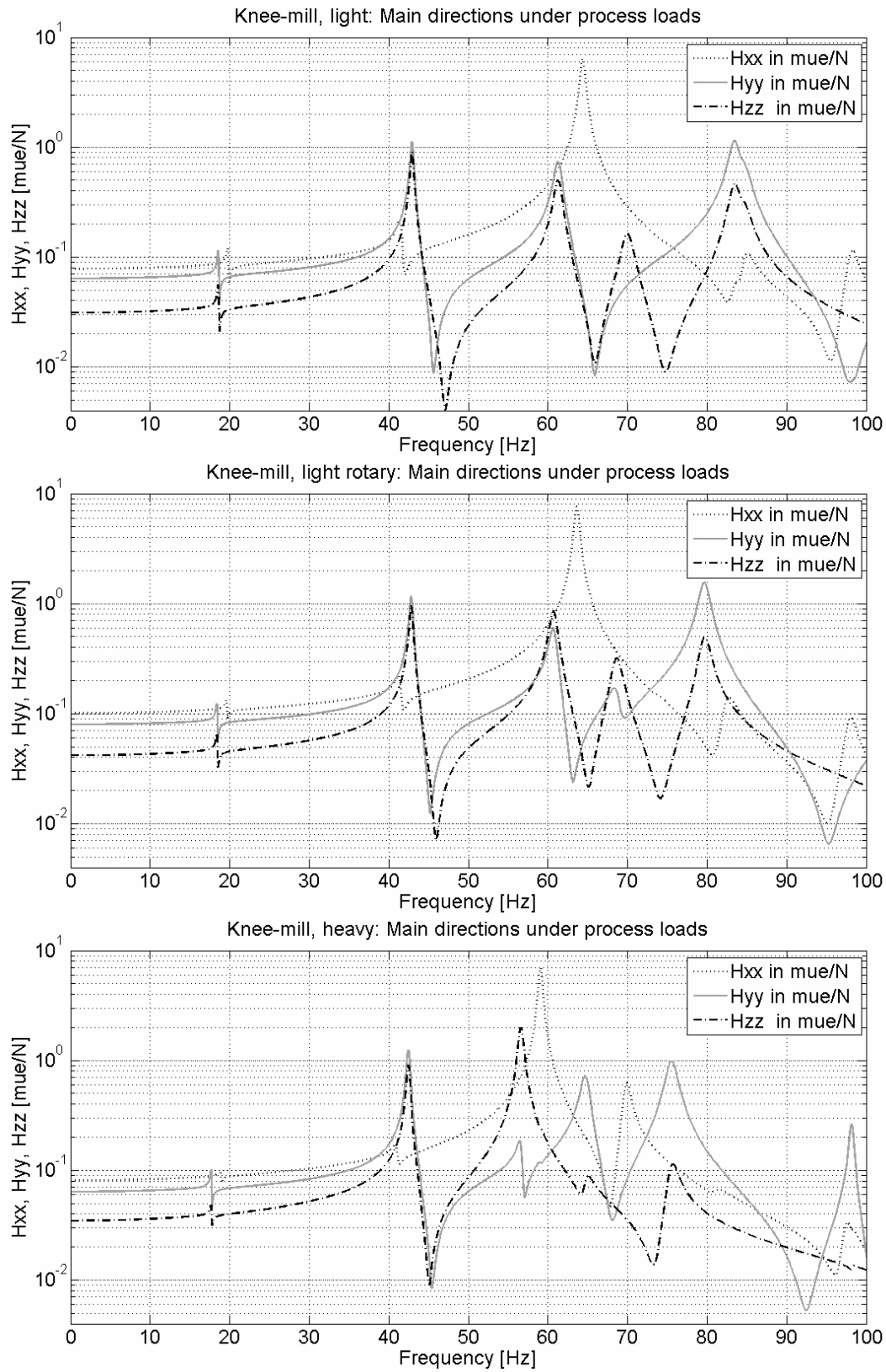


Figure 7. Eigenfrequencies of the light (above), light rotary (middle) and heavy (below) variant under process loads.

Table 3. Characteristic properties of machine variants with light and heavy spindle.

	“Heavy version”	“Light version”	“Light version with rotary head”
Configuration-influenced eigenfrequencies	5 th : 56.6 Hz	5 th : 61.3 Hz	5 th : 60.7 Hz
	6 th : 59.1 Hz	6 th : 64.4 Hz	6 th : 63.6 Hz
	7 th : 64.7 Hz	7 th : 70.0 Hz	7 th : 68.6 Hz
	8 th : 69.8 Hz	8 th : 74.3 Hz	8 th : 73.3 Hz
	9 th : 75.5 Hz	9 th : 83.5 Hz	9 th : 79.7 Hz
	10 th : 81.0 Hz	10 th : 84.7 Hz	10 th : 82.5 Hz
	12 th : 98.2 Hz	12 th : 111.6 Hz	12 th : 107.8 Hz
Cross-talk $EZ\ddot{Y}$ (static)	2.2 to 3.6 $\mu\text{m/g}$	0.24 to 0.4 $\mu\text{m/g}$	-1.40 to -1.26 $\mu\text{m/g}$

The influence of lateral offsets of the centre of gravity in relation to the drive force leads to the well-known phenomenon called cross-talk, which in this case can be quantified efficiently for the static case in values as shown in Table 3. What strikes one is that the cross-talk $EZ\ddot{Y}$ covers a much wider range on the heavy variant than on the light versions. However, the light versions differ in the amplitude and direction of the displacement of the TCP. Again, the reason for this behaviour is the additional connection between the spindle unit and the Y axis, which basically adds another elastically coupled mass to the system. When accelerated in the positive direction, the TCP has a tendency to rise because the centre of gravity of the Y axis is located higher than the point of load incidence of the drive. As the rotary unit’s centre of gravity is even lower, and the connection acts like a spring, the spindle – and with it the TCP – bounces back, which results in a more pronounced displacement to the opposite direction. Table 3 summarises the key characteristics of the three variants which are obtained by calculation. Based on these values, the variants are characterised properly and allow a well-founded evaluation of each. The time for calculating and visualising the displacements under process loads in all directions and the first 10 eigenfrequencies is about 15 seconds per variant.

5.2 Time Domain

In order to retrieve some further information on the machine’s behaviour, a linear positioning movement in the Y direction has been simulated. This simulation provides the TCP trajectory for a positioning over a distance of 0.1 m with 0.2 m/s programmed feed rate, 4 m/s² set point acceleration and a jerk limitation of 1000 m/s³. Figure 8 shows the displacement of the TCP in the Z direction over the positioning distance in the Y direction for the three machine variants. As in the quasistatic calculation, the heavy spindle variant clearly suffers most from the cross-talk effect. The rise of the TCP of the light spindle rotary head unit at the beginning of the deceleration phase can be explained by an upswing movement of the spindle around the rotary connection, forced by the unit’s significantly lower centre

of gravity. The higher amplitudes compared to the quasistatic calculations are above all due to the high jerk limitation and furthermore to the fact that the simulation takes into account the frequency dependence of the structure which intensifies the effects at certain frequencies, similar to the resonances shown in Figure 7. However, the general ranking of the cross-talk amplitudes from the calculation is confirmed by the simulation.

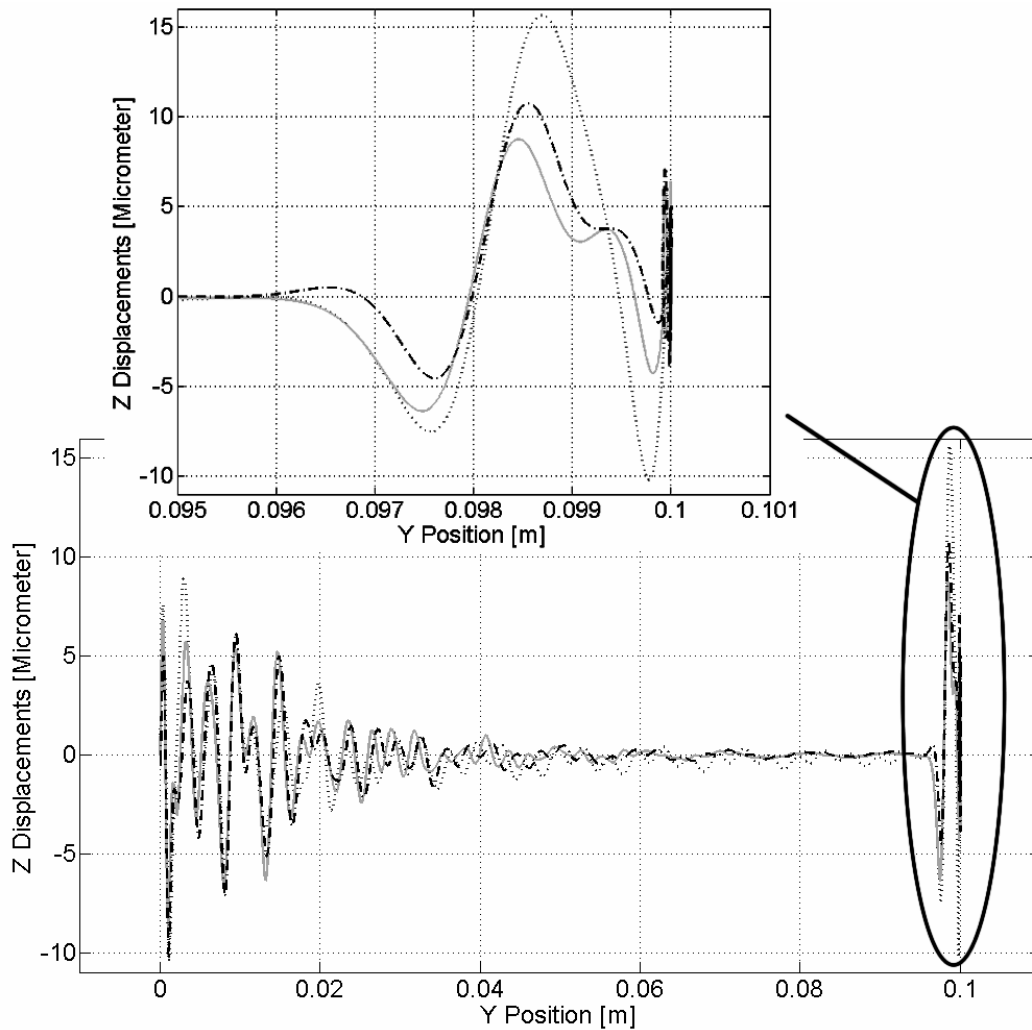


Figure 8. Simulation of the TCP's Z displacement during a linear positioning movement over 0.1 m in the Y direction.

The analysis of the discussed variants leads to the conclusion that the machine with the light spindle unit should be preferred. Its frequency properties and cross-talk behaviour are significantly better than ones of the heavy spindle variant. Furthermore, the light spindle variant does not suffer from an additional weakening by the rotary axis of the other compared variant, which introduces some more undesired effects.

Modelling the three variants and analysing their quasistatic behaviour would usually last about two hours. The time for modelling the different modules is not taken into account because this is meant to be done by the module manufacturer who provides the files with all the relevant data concerning his modules. It has to be remarked, though, that generating the closed-loop drive models and their optimised parameterisation for this simulation still necessitates a considerable amount of time and effort compared to the ones used for the calculation. This example demonstrates that the Axis Construction Kit can be used in a very efficient way for obtaining information on which decisions on the usefulness of structural variants can be based.

6 Conclusions

The presented Axis Construction Kit is a tool for obtaining reliable physical information on the behaviour of machine tool structure variants. The structure models may be built from scratch or as combinations of different module models. These module models reflect the manufacturer's experience and are stored in a module library. An appropriate structure for module models, which meets the particular requirements for usage in the domain of reconfigurable machine tools, has been applied. This efficient modelling and evaluation tool is used within the first phase of a reconfiguration methodology for RMTs. Thus, the assessment of structural variants can be based on reliable data which increases the basis of relevant information for decisions at that early stage. The validity of the calculation and simulation algorithms has been tested and proved in several cases on conventional machine tools. The verification of the results provided by the tool will be a major issue for future tests on a prototype RMT which is currently under development.

As an example case, three structural RMT variants are compared by their static and dynamic properties using the standard and advanced analysis functionalities of the Axis Construction Kit. It shows how to analyse machine structures with respect to their eigenfrequencies and the displacements of the TCP. In contrast to commercial CAM packages, it is not the geometrical correctness of the programming that is verified but the deviations due to structural influences are analysed.

The correct interpretation of the calculation and simulation results requires knowledge and experience in machine tool building. However, the intended users of this tool are engineers in manufacturing companies who will be in charge of planning a manufacturing process employing RMTs. Understandably enough, these persons often do not have the above-mentioned skills at their disposal. To assist less experienced users, future work will therefore include the development and integration of further software functionalities providing supplementary indications and advices.

7 Outlook

Unlike conventional machine tools, RMTs and their components cannot be optimised for a chosen configuration. A promising approach to enhance the properties of reconfigurable machines would be to use the control system for the compensation of structural insufficiencies. For this purpose, a control model is needed which takes into account the physics of each module and of the machine as a whole. A sufficiently detailed machine configuration file could provide data for generating a control model that compensates relevant dynamic and possibly thermal effects. In order to take into account only the necessary data, a sensitivity analysis for the considered parameters has to be conducted. For convenient and secure implementation in practice, the specified models have to be generated automatically. Also, the integration into the control, including the required control parameter set, has to be done automatically or with the aid of a configuration tool.

8 References

- Abele, E. and Wörn, A. (2004): Chamäleon im Werkzeugmaschinebau. *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb* (v99), pp152–156.
- Altintas, Y. and Cao, Y. (2005): Virtual Design and Optimization of Machine Tool Spindles. *Annals of the CIRP* (v54, n1), pp379–382.
- Altintas, Y.; Brecher, C.; Weck, M.; and Witt, S. (2005): Virtual Machine Tool. *Annals of the CIRP* (v54, n2), pp651–674.
- Bamberg, E. (2000): Principles of Rapid Machine Design. Dissertation, Massachusetts Institute of Technology.
- Bianchi, G.; Paolucci, C.; Van den Braembussche, P.; and Van Brussel, H. (1996): Towards Virtual Engineering in Machine Tool Design. *Annals of the CIRP* (v45, n1), pp381–384.
- Brecher, C.; Weck, M.; and Müller-Held, B. (2005): FE-Ergebnisdarstellung mit Hilfe der Virtual Reality und Maschinenbeurteilung im Arbeitsraum. *Proceedings of WZL Seminar – Messtechnik und Strukturanalyse von Werkzeugmaschinen*, Aachen.
- Chen, L.; Xi, F.; and Macwan, A. (2005): Optimal Module Selection for Preliminary Design of Reconfigurable Machine Tools. *Transactions of the ASME* (v127), pp104–115.
- Gu, P. and Slevinsky, M. (2003): Mechanical Bus for Modular Product Design. *Annals of the CIRP* (v52, n1), pp113–116.
- Heisel, U. and Meitzner, M. (2002): Technische Wissensbibliothek zur Rekonfigurierung von Fertigungssystemen. *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb* (v97, n7–8), pp397–399.
- Heisel, U. and Stehle, T. (2006): Intelligente und vorausschauende Produktion. *Dima* (n5), pp6–16.

- ISO 23570-1:2005: Industrial Automation Systems and Integration – Distributed Installation in Industrial Applications; Part 1
Sensors and Actuators
- ISO 23570-2:2005: Industrial Automation Systems and Integration – Distributed Installation in Industrial Applications; Part 2
Hybrid Communication Bus
- Jedrzejewski, J.; Kowal, Z.; Kwasny, W.; and Modrzycki, W. (2004): Hybrid Model of High Speed Machining Centre Headstock. *Annals of the CIRP* (v53, n1), pp269–274.
- Kircher, C.; Seyfarth, M.; and Wurst, K.-H. (2004): Modellbasiertes Rekonfigurieren von Werkzeugmaschinen. *wt Werkstattstechnik online* (v94, n5), pp285–288.
- Kircher, C. and Wurst, K.-H. (2006): Modulkonzept für rekonfigurierbare Bearbeitungs- und Steuerungssysteme. *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb* (v101), pp360–365.
- Koren, Y.; Heisel, U.; Jovane, F.; Moriwaki, T.; Pritschow, G.; Ulsoy, G.; and Van Brussel, H. (1999): Reconfigurable Manufacturing Systems. *Annals of the CIRP* (v48, n2), pp527–540.
- Landers R.; Min, B.; and Koren Y. (2001): Reconfigurable Machine Tools. *Annals of the CIRP* (v50, n1), pp269–274.
- Lorenzer, T.; Kunz, A.; and Wegener, K. (2007): Umrüstbarkeit macht flexibel. *WB Werkstatt + Betrieb* (v140, n3), pp18–23.
- Moon, Y.-M. and Kota, S. (2002a): Generalized Kinematic Modeling of Reconfigurable Machine Tools. *Journal of Mechanical Design* (v124), pp47–51.
- Moon, Y.-M. and Kota, S. (2002b): Design of Reconfigurable Machine Tools. *Journal of Manufacturing Science and Engineering* (v124), pp480–483.
- Moon, Y.-M. (2006): Reconfigurable Machine Tool Design. In: Dashchenko, A.I. (Ed.): *Reconfigurable Manufacturing Systems and Transformable Factories*. Springer, pp112–139.
- Neugebauer, R.; Weidlich, D.; Kolbig, S.; and Polzin, T. (2005): VR-unterstützte Entwicklung von Werkzeugmaschinen. *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb* (v100, n1–2), pp59–65.
- Pasek, Z.J. (2006): Challenges in the Design of Reconfigurable Machine Tools. In: Dashchenko, A.I. (Ed.): *Reconfigurable Manufacturing Systems and Transformable Factories*. Springer, pp141–154.
- Runde, C. and Fisser, F. (2004): Einsatz der Digitalen Fabrik und Virtuellen Realität im Werkzeugmaschinenbau. *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb* (v99, n4), pp192–195.
- Shabaka, A. and ElMaraghy, H.A. (2005): Mapping Products Machining Requirements and Machine Tools Structure Characteristics in RMS. In: Zaeh, M.F. and Reinhart, G. (Eds.): *1st International Conference on Changeable, Agile, Reconfigurable and Virtual Production*. Herbert Utz, pp289–296.
- Vichare, P.; Nassehi, A.; Kumar, S.; Newman, S.; Zheng, L.; and Dhokia, V. (2007): Towards a STEP-NC Compliant Model for Representation of Machine Tools. *Proceedings of the DET2007*, Bath.

- Weikert, S. (2000): Beitrag zur Analyse des dynamischen Verhaltens von Werkzeugmaschinen. Dissertation ETH, 13596.
- Weikert, S.; Bossoni, S.; and Wegener, K. (2007): Evaluation of Machine Tool Concepts under Friction Influences. *Proceedings of the ASPE 2007 Annual Meeting*, pp163–166.
- Wörn, A. and Bauer, J. (2006): Verwandlungskünstler – Trendbericht: Rekonfigurierbare Werkzeugmaschinen. *WB Werkstatt + Betrieb* (n9), pp58–67.
- Wurst, K.-H.; Heisel, U.; and Kircher, C. (2006): (Re)konfigurierbare Werkzeugmaschinen – notwendige Grundlage für eine flexible Produktion. *wt Werkstattstechnik online* (v96, n5).
- Yigit, A.S. and Ulsoy A.G. (2002): Dynamic Stiffness Evaluation for Reconfigurable Machine Tools including Weakly Non-Linear Joint Characteristics. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (v216, n1), pp87–101.
- Zaeh, M.F. and Baudisch T. (2003): Simulation Environment for Designing the Dynamic Motion Behaviour of the Mechatronic System Machine Tool. *Proceedings of the Institution of Mechanical Engineers* (v217, Part B), pp1031–1035.
- Zaeh, M.F. and Oertli, T. (2004): Finite Element Modelling of Ball Screw Feed Drive Systems. *Annals of the CIRP* (v53, n1), pp289–293.
- Zirn, O. and Weikert, S. (2006): *Modellbildung und Simulation hochdynamischer Systeme*. Springer.

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