Simulation environment for designing the dynamic motion behaviour of the mechatronic system machine tool

M F Zaeh and **T Baudisch***
Institute for Machine Tools and Industrial Management, Technische Universität München, Munich, Germany

Abstract: Machine tools consist of mechanical and electronic components and software, and thus constitute mechatronic systems. To make sure that they work reliably in the overall system these different components have to be designed in coordination. This process is complicated by the fact that virtual prototyping is becoming increasingly important in machine tool design and every development department employs different software tools, e.g. finite element method, multibody system simulation, computer aided control engineering software, etc. Moreover, every department has its own method of setting up models within these programs. The result is that various sets of data are produced that are mutually incompatible due to different modelling methods. This paper describes a new method for setting up a model for the mechatronic system machine tool, with special emphasis on the design of its motion dynamics. The main objective of the method is to standardize the model set-up within the different simulation tools with a view to producing reusable data. A concept for data management and provision is also presented.

Keywords: machine tool, computer aided engineering, simulation, mechatronic overall model

1 INTRODUCTION

Individual customer wishes, changing requirements and technical developments associated with decreasing innovation cycles, and increasingly fierce price wars on the market have prompted many machine tool builders to reorganize their design processes. A good example of this trend is considered in the following, i.e. the customer's request for machine tools that can increase productivity while providing unchanged or even superior accuracy. This requirement directly affects the design of the feed drive axes (Fig. 1). More and more machine tool manufacturers are now focusing on virtual prototyping with a view to reducing development times and development costs. The objective is to analyse and optimize the dynamic behaviour of machine tool design on a model so that the first hardware prototype optimally fulfils the requirements and can therefore be sold without adaptations.

Typical introduced simulation tools are programs for the simulation of the kinematics, finite element method (FEM) software, multibody system simulation (MBS) software, computer aided design (CAD) software and computer aided control engineering (CACE) software. Kinematic simulation software permits an accurate analysis of the kinematics and is used for detecting collisions of moving parts and for testing numerically controlled (NC) programs. The field of application of the FEM is the calculation of static (deformation of components, internal stress situation) and dynamic (eigenfrequencies and mode shapes) behaviour of single mechanical components or assemblies. MBS software is used for analysing the dynamic behaviour of mechanical systems executing large, non-linear movements and CACE software is used for designing and analysing control systems [**1**].

The application of the software can be characterized as follows: each development department applies its own simulation software based on its department-specific tasks. CAD, kinematics simulation, FEM and MBS software are commonly used in the mechanics design department. The problem in the field of mechanics simulation is that each designer has his or her own method of setting up models. This means that each designer selects component boundaries and has a particular method for

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[*] *Corresponding author: Institut für Werkzeugmaschinen und Betriebswissenschaften, Technische Universität München, Boltzmannstrasse 15, D-85748 Garching, Germany.*

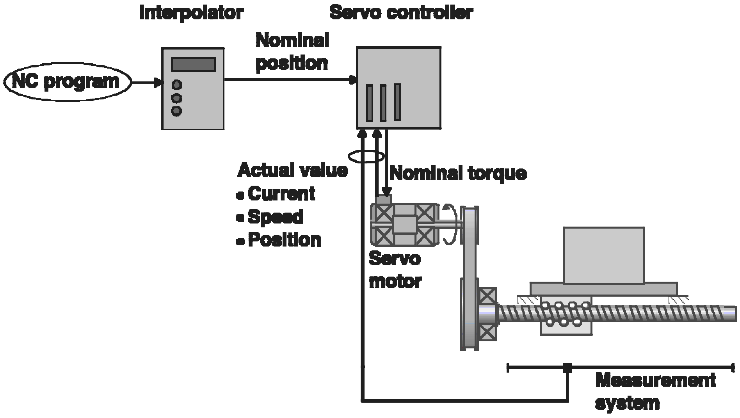


Fig. 1 Structure of feed drives

modelling the interfaces between components in the simulation software. Consequently, the data generated for one simulation tool cannot be reused for another tool. The application of simulation methods in the electronics design department is another example of the same problem. One essential task in the design of the electronics is the selection and parameterization of the control system. CACE software is typically used for parameterization. A model of the mechanics of the feed drive axes is required for parameterization of the control system. A simplified model of the mechanics is usually produced in the electronics department for this purpose. However, a detailed model is also made available by the mechanics department. The situation therefore arises in which redundant data are generated, thus increasing the probability of errors. Another problem is that the electronics-oriented description of the mechanics in the form of differential equations or transfer functions is generally difficult for mechanical engineers to understand.

As explained above, customer requirements regarding the motion dynamics of machine tools will continue to increase and machine tool builders are going to have to accommodate them. Here it must be taken into consideration that the generation of the feedforward motion of machine tools depends on many components emanating from different disciplines, e.g. bed, spindles and slides as examples of mechanical components, servo controllers and servo motors as examples of electronic components and the NC kernel as an example of the information technology components (Fig. 1). For further enhancement of the motion dynamics, these components and the assembled substructures have to be designed in coordination—as a mechatronic overall system—in the future [**2**–**4**]. This puts new requirements on today's simulation aided design process for an integrated model set-up. A method is presented below for setting up models such that the generated data can be reused in different simulation tools and in different development departments.

2 METHOD FOR AN INTEGRATED MODEL SET-UP

A new method for an integrated model set-up is explained in the following. The idea is to build a machine tool model using so-called mechatronic simulation modules. What are mechatronic simulation modules?

Subsequent to the conceptual design phase, the concept is partitioned into single components. These components can be predefined in the case of well-known systems, such as feed drive axes. The advantage of a component is that it has a fixed boundary and interfaces to other components can be specified for this boundary. The modelling of these interfaces can also be standardized. The objective of this procedure is to make a great deal of the data that is generated for describing a component in one simulation program reusable for other simulation programs. Thus, for example, the frequency response modes from an FEM analysis can be reused for modelling this component as a flexible body in an MBS simulation. All the data required for describing a component in different simulation programs are combined in a so-called mechatronic simulation module. Mechatronic simulation modules organize their data in views such that all the data that are necessary for describing a component in one special simulation program are contained in that view (Fig. 2).

A special view of the component can easily be set up in the associated simulation program based on the data contained in the views of the mechatronic simulation modules. A component can be coupled with other components without having to make modifications, thanks to standardized interfaces. These simulation method-specific models can in turn be linked using standardized interfaces. This would allow the electronics design department, for example, to link its models to models from the mechanics design department [**5**]. This method of procedure makes modelling tasks much

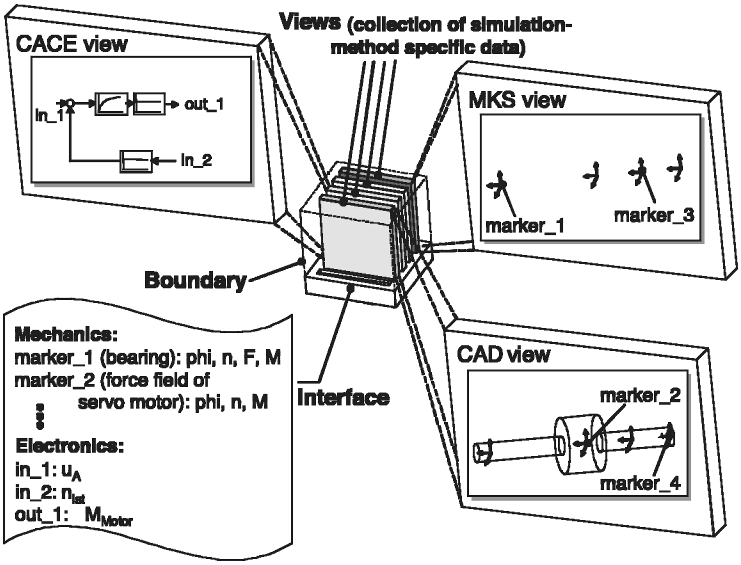


Fig. 2 Example of the mechatronic simulation module 'servo motor rotor'

more efficient, optimally supports the available department-specific expertise and thus improves the quality of the simulation results.

3 MECHATRONIC SIMULATION MANAGEMENT SYSTEM

Interdisciplinary collaboration in the field of simulation based on the new method requires a software tool that assists the application of the method. The tasks to be fulfilled by this tool—the mechatronic simulation management system—range from supporting the designers by generating the different views of a mechatronic simulation module and making all the existing information on a component available to them, documenting the model set-up and managing all the data that accumulate. The tool must therefore comprise two modules, a library and a simulation project module (Fig. 3). The task of the library module is to support the generation of the component-specific data and to manage these data. The library module offers a window in which the mechatronic simulation modules can be generated for this purpose. For each entry of a new mechatronic simulation module the library opens a form containing all the simulation tools used in the design process. The simulation tools are arranged in groups according to the mechatronic disciplines for whose design they are mainly used. There is a separate form for each simulation tool. All the data generated for a component are entered in the central database using these special forms. When the data for a component are entered in one simulation method specific form, they are made available to all other simulation methods that can make use of these data. This process is based on an allocation table (Fig. 4).

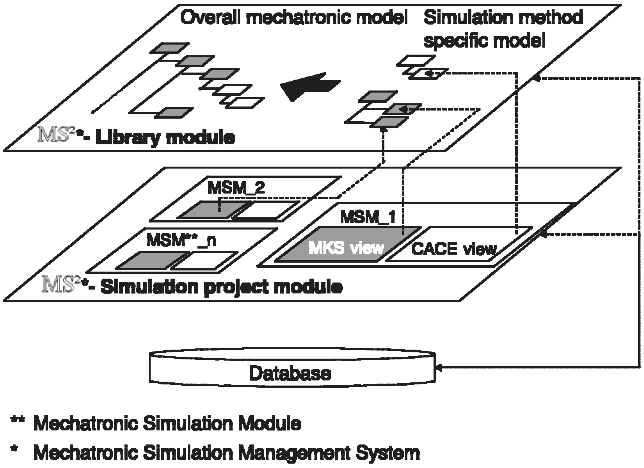
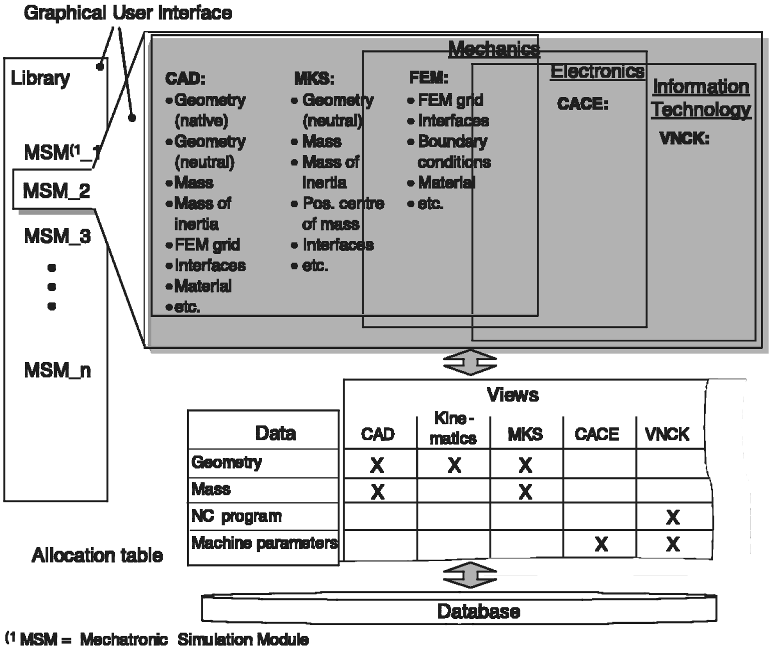


Fig. 3 Structure of the mechatronic simulation management system

The task of the simulation project module is to document the model set-up and to manage the associated simulation results. The structure of a subsystem model is represented by a tree structure for this purpose. Each node of the tree structure corresponds to the simulation method specific form of the associated mechatronic simulation module from the library module. This makes it easy for designers to understand how the model is set up.

Furthermore, both modules offer extensive viewing and documentation functions and allow the designers direct data access to all task-specific essential data. Data storage is not included in the tasks of the mechatronic simulation management system. A commercial PDM system can be used for this purpose, for example. The mechatronic simulation management system is therefore a tool that



Data	CAD	Kinematics	MKS	CACE	VNCK
Geometry	X	X	X		
Mass	X		X		
NC program					X
Machine parameters				X	X

Fig. 4 Structure of the library module of the mechatronic simulation management system

can easily adapt commercial data management systems into the special requirements of mechatronic machine tool design.

4 REALIZATION OF MECHATRONIC SIMULATION MODULES

The partitioning of the real system machine tool into mechatronic simulation modules is oriented towards the interfaces of the real system. Thus, for example, there are interfaces between the interpolator and the servo controllers and other interfaces between the control systems and the servo motors (Fig. 1). This gives rise to the mechatronic simulation modules interpolator and control systems. Suitable interfaces for partitioning the mechanics include bearings, linear systems and bolted connections. Consequently, servo motor housings, servo motor rotors, pinions, wheels, ball screws, spindle nuts and slides are generated. Measurement systems also have to be considered as interfaces between the mechanical and electronic or IT components. These components are the classical mechatronic simulation modules for designing the dynamic motion behaviour of machine tools.

As mentioned above, interfaces have to be determined for each component. The following interfaces can be defined for the mechatronic simulation modules for modelling feed drive axes:

1. *Interpolator*: interfaces for input signals (in): NC program code; interfaces for output signals (out): nominal axis positions.
2. *Servo controller*: in: nominal axis position, actual axis position, actual speed and actual current; out: nominal current.
3. *Servo motor housing*: in: nominal current, nominal speed; out: actual current, actual torque.
4. *Mechanical components*: in: actual torque, outer forces/torques, e.g. friction, process force; out: reaction force/torque, actual position.

A concept for integrated modelling of these interfaces has been developed. Special attention was paid to integrated modelling of the different mechanical views. Because mechanical modelling requires that interfaces be modelled as coordinate systems and that kinematic and/or force constraints be defined between their elements, positioning of the coordinate systems also had to be standardized [**5**].

Applying the method presented allows modular simulation components to be generated that can be used for setting up task-specific simulation models. A kinematic model of the mechanics can be set up quite easily using CAD data, for example. This kinematic model can be coupled with the predefined mechatronic simulation module of a real interpolator, called the virtual NC kernel (VNCK), also developed within the mechatronic simulation environment, for the purposes of testing an NC program [**6**]. A large amount of the data generated for the CAD and kinematic model can be reused later for setting up an MKS model of the mechanics. Coupling this MKS model with the VNCK and the mechatronic simulation modules of the servo controllers allows detailed analysis of the duration of an NC program as well as of the accuracy of the tool centre point along the programmed tool path.

5 CONCLUSION

This method for building simulation models efficiently provides the machine tool industry with a powerful tool for identifying the optimum configuration of a machine tool to customer specifications. A method involving reusable simulation components is presented with a view to reducing the effort required for the highly time consuming set-up of mechatronic models. A high level of modularity coupled with effective interfacing are the key characteristics of a mechatronic simulation environment that is able to utilize the expertise of personnel in the various specialist departments to the full.

REFERENCES

1 **Großmann, K.** Was ist, soll und kann die virtuelle Werkzeugmaschine? In Proceedings of 4th Dresdner WZM-Fachseminar on *Was kann die virtuelle Werkzeugmaschine?*, Dresden, Germany, 20–21 June 2002.

2 **Berkemer, J.** and **Knorr, M.** Gekoppelte Simulation von Maschinendynamik und Antriebsregelung bei linearangetriebenen Werkzeugmaschinen. *wt Werkstattstechnik*, 2002, **92**(5), 226–235.

3 **Pritschow, G.** and **Bretschneider, J.** A self-tuning controller for digitally controlled electromechanical servo drives in machine tools. *Ann. CIRP*, 1999, **48**(1), 307–312.

4 **Schäfers, E., Hamann, J.** and **Tröndle, H.-P.** Analyse, Simulation und Regelung von Werkzeug- und Produktionsmaschinen. In Proceedings of First International Symposium on *Mechatronics*: *Advanced Driving Systems '02*, Chemnitz, Germany, 21–22 March 2002, pp. 183–192.

5 **Baudisch, T.** Simulationsumgebung zur Auslegung der Bewegungsdynamik des mechatronischen Systems Werkzeugmaschine. *Utz*, München, 2003 (to be published).

6 **Reinhart, G.** and **Baudisch, T.** Mechatronic Simulation Environment for Machine Tools. In Proceedings of 8th IEEE Conference on *Mechatronics and Machine Vision in Practice '01*, Hong Kong, 27–29 August 2001, pp. 217–221.