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Decision-making Aid for the Design of Reconfigurable Machine Tools

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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 re-configuration of machine tools. This paper presents a software based methodology for designing and evaluating the performance and conformance to requirements at an early stage. A machine model can be assembled by accessing a module library, which contains models of all available physical modules. The machine behaviour of the resulting configuration is tested, which provides reliable information on the physical machine properties. Different variants can be set up and quickly and easily analysed, significantly improving the data basis on which important and far-reaching decisions have to be made.

Keywords: Reconfigurability, machine design, modelling

1 Introduction

Nowadays, manufacturing industry is facing turbulent and quickly changing business environments, which has a growing impact on the manufacturing system requirements. Investments in expensive product oriented manufacturing systems with limited adaptability will not pay off any more, when product life time and batch sizes decrease. Furthermore, new manufacturing processes or materials might require adaptations or changes at the machines. Currently used machines are not, or only in a very limited range, capable of dealing with changing requirements with respect to capacity, functionality, technology or machine structure.

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To fulfil the need for quick adaptation and change, Koren, *et al.* (1999) propose reconfigurable manufacturing systems (RMSs) which are at the outset designed with adjustable resources. Their major components at the machine level are reconfigurable machine tools (RMTs) which are designed for specific operations. Therefore, RMTs represent cost efficient and effective manufacturing devices (Landers, *et al.*, 2001).

In recent years, first types of reconfigurable machine tools have been developed. Most of them are a result of industry supported research projects. They are reconfigurable in terms of either technology or geometry or both (Wörn, Bauer, 2006). Although there has been some progress in developing modular machines that can be reconfigured, there are still many open 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, *et al.*, 2001). This starts from efficient simulations of the properties of a new machine configuration at a very early stage to provide reliable information for design decisions and progresses up to configuration tools for an easy and rapid starting up of the reconfigured machine.

2 Design Procedure for Reconfigurable Machine Tools

Reconfigurable machine tools have to be designed for the purpose of being reconfigured by the machine user. The reconfiguration must be feasible with moderate means and knowledge and experience of production engineers and machine operators. The machine or module manufacturer/supplier only step in if necessary. As the inital configuration of a reconfigurable machine and any following reconfiguration do not differ significantly, machine manufacturer and user can use the same tools for conceiving and evaluating possible machine structures. Nevertheless, machine or module manufacturers need additional tools, so that every physical module is delivered with a corresponding virtual model.

These physical and virtual module libraries facilitate and accelerate the reconfiguration of machine tools in compliance with requirements. The (re)configuration process consists of three major phases, in which different tools are used (Fig. 1). All tools access the virtual machine model, which evolves during this process and is consistently updated.

2.1 Definition of the Axis Configuration

A virtual module library contains all available physical modules and provides the necessary data for preliminary simulation. At the design stage, the configuration of axes and spindles of the machine tool are chosen by simply selecting the modules from the library and connecting them. Thus, a virtual model of the entire machine is generated, which is sufficient for the calculation or simulation, respectively, of its key properties. Hence, this configuration can be tested on static, dynamic and, if required, thermal behaviour in order to obtain reliable information for decisions concerning the machine structure.

Good performance of the machine across the working range is a crucial criterion for the quality of the reconfigured machine structure. Quasistatic evaluation techniques can be used in order to accelerate the performance evaluation at varying positions in the work space. This allows the machine tool user to evaluate the reconfigured machine with respect to the requirements.

By using process simulation, further performance data can be obtained. With given operation requirements and drive properties, the throughput or cycle times can be estimated. This additionally obtained data concerning the manufacturing capacity makes further decisions even more well-founded.

After analysing these preliminary estimations the decision which variants to keep is more objective and certain than without this information. Therefore, the number of chosen variants should be manageable, so that more precise analyses without excessive deployment of resources are possible.

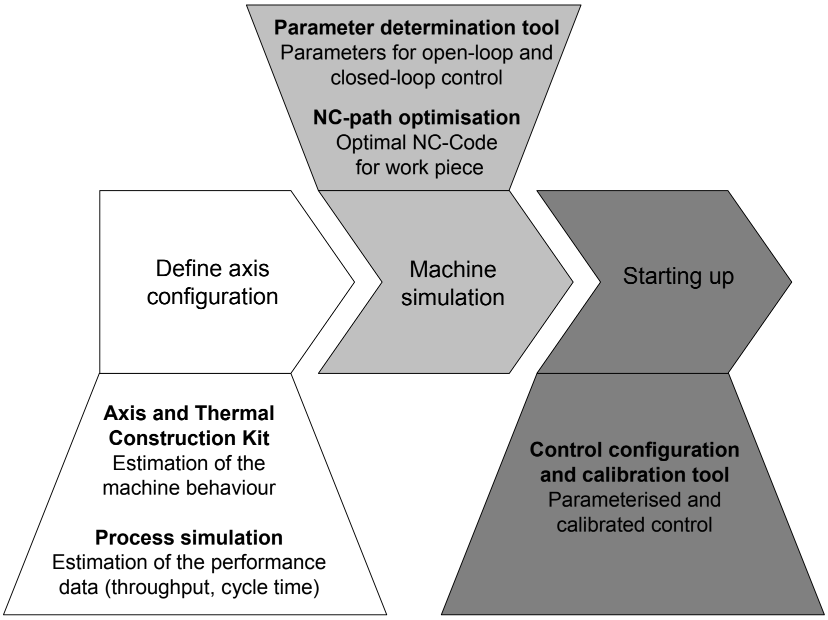

Fig. 1. Necessary software tool support for machine tool users during the reconfiguration process

2.2 Machine Simulation

After the configuration of the machine has been defined, the necessary data for the commissioning is determined. The initial data has to be provided by the module manufacturers, who have the means describe the modules very precisely, using *e.g.* FEM simulations or experiments.

Of particular importance is the uncomplicated configuration and calibration of the control. Therefore, once the machine model has been set up, the parameters for the control have to be determined. Those parameters that are not already given in the single module models must be deduced from the provided data and from the results of the machine tool simulations, using the formerly established machine model. These values are written into a control configuration file, which thus includes all control parameters that are needed for the calibration of the control.

Single aspects may require specific simulations based on data of the provided module models, as already Bamberg (2000) demonstrated for eliminating variants at early stages. In order to ensure a quick and correct reconfiguration of the physical machine, this step has to be prepared as much as possible in advance.

With a detailed machine model, which already exists at this stage, it is possible to run an NC-path optimisation (Zaeh, Baudisch, 2003), even before the real machine has been set up. Correct and efficient NC-programs contribute to short ramp-up time which is one of the characteristics of RMTs and RMSs.

However, all time-based simulations can only provide good results, if the input data is sufficiently accurate. Substantiated evaluations and comparisons require equivalent models at a similarly detailed level. Otherwise there is a serious risk of errors in comparing and interpreting the obtained information.

2.3 Commissioning of the (Re-)Configured Machine

In the final phase the machine control has to be configured by the user. As this procedure is repeated various times during a machine's life-cycle, support by an adequate software tool is inevitable for efficient commissioning.

The control parameters of the machine tool have to be adjusted to the new configuration of the machine structure. As estimates of the parameters have been obtained during the second step, the entire set can be transmitted to the control. Geometrical constraints like the work space boundaries will not necessitate supplementary correction. Others, like the gains, might need separate adjustment and calibration which is supported by a control configuration and calibration tool.

The presented methodology is applicable for the development of reconfigurable machine tools consisting of stand-alone modules. Such modules are explicitly designed for this purpose, and the manufacturer provides all necessary data for efficient use.

In the following, a software tool for the first phase of the (re)configuration process is presented. The Axis Construction Kit is proposed as source of extended information based on calculation and simulation. It aims at supporting engineers in decisions on eliminating variants.

3 The Axis Construction Kit as Decision-making Aid

Decisions on the structure of a machine have to be made at an early stage of the design process. As the structure's impact on machine performance and accuracy is considerable, its determination is crucial for the machine tool. This issue is particularly important for a machine tool that is assembled from ready-to-use modules which cannot be optimised for every possible configuration. Unfortunately, at that early stage there are only few data available which these decisions can be relied upon.

The Axis Construction Kit enables the machine tool user to obtain reliable information on the expected machine behaviour of different machine configurations in very short time. These configuration variants are generated for the available modules from the models in the library. By this means, several structure variants of machine tools can efficiently be modelled and evaluated which eliminates some uncertainties, *i.e.*, provides additional information for well-founded decisions. As the library is expandable, the machine tool user always disposes of all relevant module models so that the evaluation can be done at every reconfiguration.

The Axis Construction Kit, especially designed for modelling machine tools, has been developed at the IWF and 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, which represent important conveniences for its further development.

3.1 Functions

The Axis Construction Kit consists of several functions which are consecutively performed during the modelling process. After starting the **Axis Construction Kit** window, the user first selects the spindle alignement to determine the machine coordinate system. Next, he can chose whether to use a predefined machine configuration or to begin a new machine design. The immediate visualisation of the machine during every step helps to avoid geometrical input errors in the structure design.

In the **Machine Definition** menu (Fig. 2), the machine structure is assembled. This is done by adding, positioning and sizing all machine components like moving axes, spindles and drives. 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 of the represented machine components. Whenever module models are available, they can be included in a module library from which the desired modules are chosen for assembling the virtual machine. Such a library usually contains several modules that differ in dimensions, weight and stiffness or other key characteristics, *e.g.* a direct or indirect position feedback system. Reconfigurable machine tools should mainly consist of these modules which facilitates the reconfiguration for the user.

The **Drive Definition** menu is used for defining the moving axes's drives and position feedback systems and for setting their properties. In this menu the drive type, reference bodies for drive and position feedback system and their detailed locations are chosen. For each drive type the necessary information is queried, so that the impact of the defined drives on the system can be considered immediately.

In a similar manner, the couplings between the different components, drives and the base are defined in the **Coupling Definition** menu. Different types of couplings can be chosen, *e.g,* for linear guideways of moving axes or for the basement fixation. In this function, the system matrices (mass, stiffness, damping) for the machine model which are needed for the calculation of the static displacements of the Tool Centre Point (TCP) at the defined positions across the work space are generated. These positions as well as the information and figures to be displayed are set in the **Output Definition** menu.

Once the machine model has been defined and all output settings are done, the calculation of the machine properties can be started by using the **Calculation** menu. Thus the user obtains, besides the displacement under gravitational, process and inertial loads, the properties of the machine in the frequency domain, *i.e.*, its eigenfrequencies and eigenvalues.

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 test trajectory with given parameters (*e.g.* positioning length, velocity, acceleration) and displays them as figures, which simplifies the interpretation.

The possibility to include ready-to-use module models in a library significantly reduces the modelling time compared to conventional modelling of each component.

As the properties and parameters of these modules are determined by the manufacturer, the user should rely on accurate data, which improves the quality and reliability of the obtained data and therefore of the decision based on these latter.

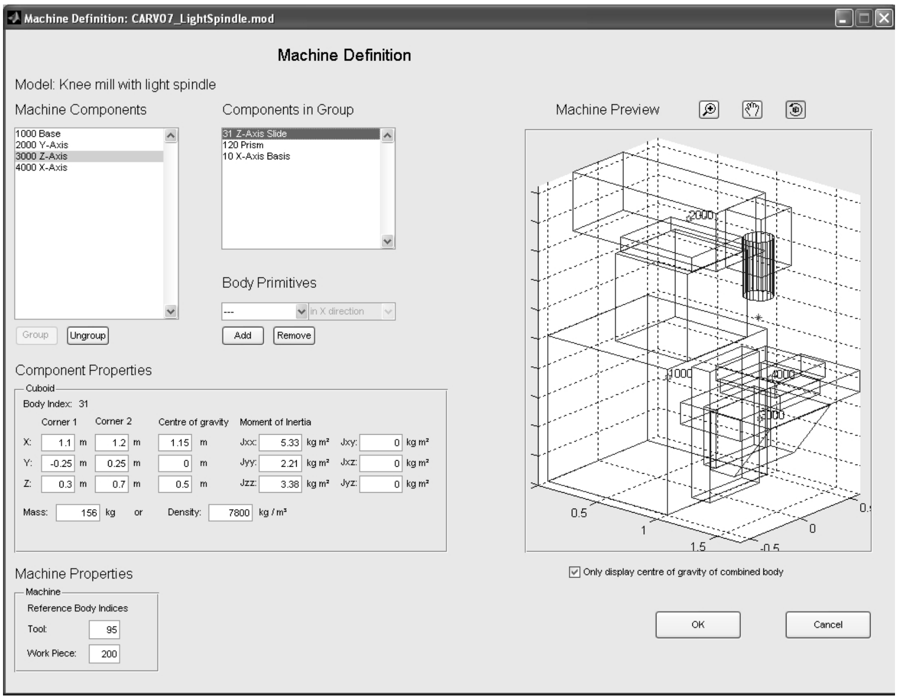

Fig. 2. Definition of the machine configuration for the Axis Construction Kit

3.2 Significance of Retrieved Information

The information, which is needed to evaluate a machine configuration, is provided by the Calculation and the Simulation menu. As mentioned before, the static and dynamic properties of the machine strucutre are calculated so that the user disposes of physical information for the description of the machine behaviour. The Axis Construction Kit calculates the displacement of the TCP in the workpiece coordinate system under given loads on a chosen set of points. Generally one would try to cover the work space chosing the extremal values, which gives an idea of the variance range.

At he same step, the frequency properties of the structure are calculated, so that eigenfrequencies and mode-shapes of the different variants can be compared. By knowing these values, an experienced designer gets a quite clear idea of the expected capacity of the considered machine, especially in comparison to other variants.

The simulation of the tool moving along a representative path allows to track the displacements of the TCP in all 3 dimensions at the same time. Significant systematic path deviation due to dynamic loads can be detected very early.

It has to be added that assessment of machine tool concepts using simulated TCP trajectories has to be done with caution and should mainly be applied for comparisons. The models that are used for the control and the drives in these simulations are kept on a quite basic level in order to reduce the number of parameters to be adjusted.

All this physical information is obtainable within a very short time and available at an early stage of the machine design. The actual calculations and simulations take a few seconds while 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 supports the user in making well-founded decisions at a stage, where the choice of the machine configuration and its basic conceptual parameters is made. Its impact on the machine behaviour is crucial, however, once determined, it is very complicated and expensive to change. Hence, significantly better, *i.e.* suited for given tasks, machine structures can be obtained from the beginning on when decision-makers are provided with reliable information at an early stage.

4 Example

As different variants can be set up and analysed quickly and easily, it is possible to obtain important information on their behaviour very efficiently. The impact of a certain configuration on the resulting static and dynamic properties can be evaluated and compared with the alternatives, *e.g.*, linear axes with small and large distances between the guideways or light and heavy modules. On the basis of the latter example, the efficient use of the Axis Construction Kit is demonstrated in the following. We consider the configuration of a knee-mill machine which is forseen to be equipped with two different spindles, however, the work space dimensions are given and cannot be altered. Table 1 shows the key characteristics and main differences between the resulting two variants.

Table 1. Main parameters of two different spindles for a knee-mill machine

	"Light version"	**"Heavy version"**
Spindle mass	30 kg	80 kg
Mass of spindle housing	35 kg	110 kg
Work space	500x400x400 mm^3	

By replacing the light spindle with a heavier spindle, the mass of the spindle unit as well as its centre of gravity change. The variants are evaluated in regard to the criteria cross-talk-effects (*e.g.* vertical displacement when accelerating in Y-direction), frequency dependent (dynamic) displacements of the TCP in the workpiece coordinate system due to process loads, eigenfrequencies and their corresponding modes.

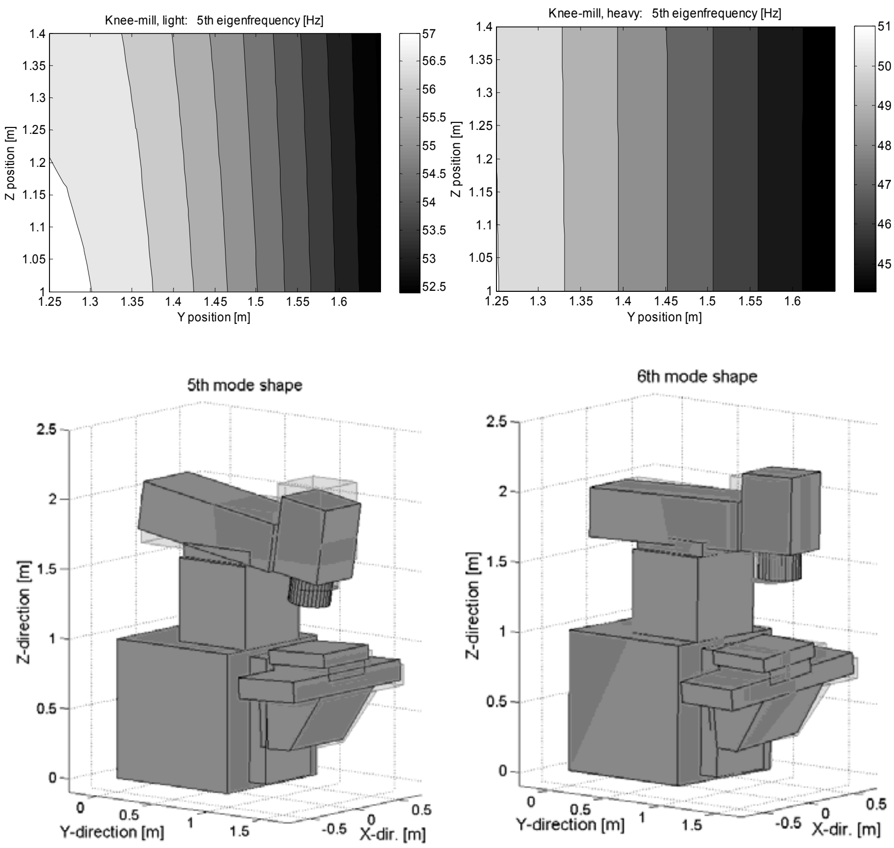

Fig. 3. Above: Distribution of 5th eigenfrequency for light (left) and heavy (right) spindle unit variant. Below: Mode shapes of the 5th (left) and 6th (right) mode (visualisation for the variant with heavy spindle unit)

As shown in Fig. 3, the fifth and the sixth eigenfrequency show different values. The eigenfrequencies 1 to 4 and 7 to 12 which also have been investigated remain rather unchanged due to the changes in the configuration. The corresponding modes 5 and 6 are shown at the bottom of Fig. 3.

When evaluating different modes the corresponding mode shapes lead to an effect between tool and work piece. The frequency dependent dynamic compliances due to process forces between tool and work piece for the two variants are shown in Fig. 4. As a result of the changing configuration, the peaks at 49 and 52 Hz corresponding to the 5th and 6th mode shape move to 56 and 57 Hz.

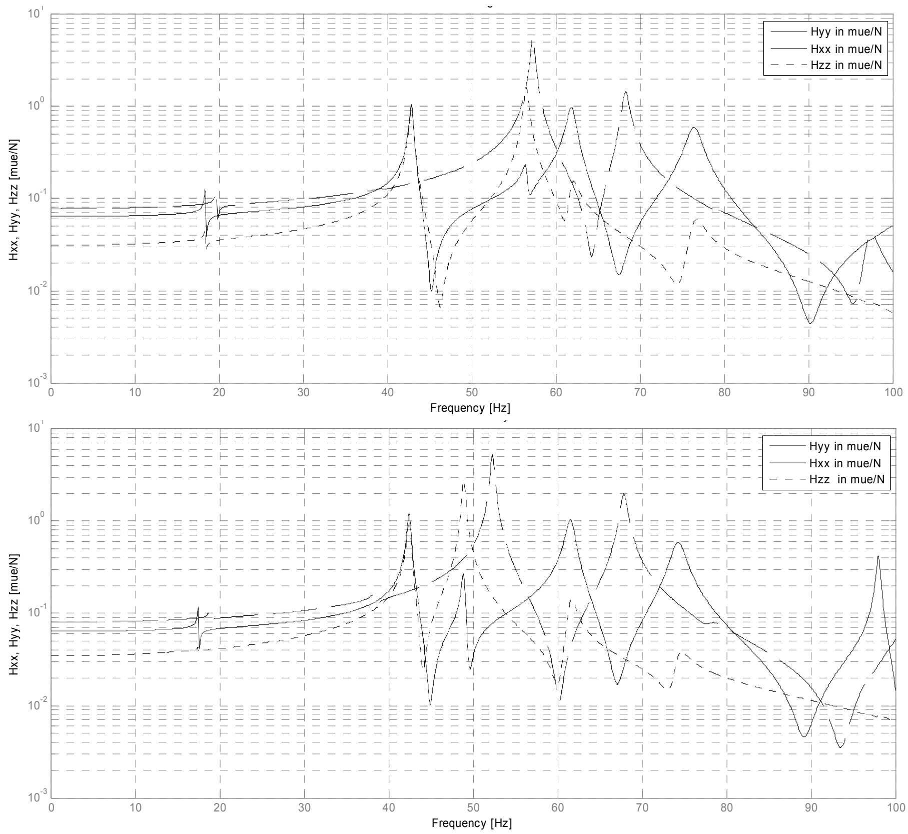

Fig. 4. Eigenfrequencies of the light (above) and heavy (below) variant under process loads

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 2. The table summarises the key characteristics of the two variants, which are obtained by calculation. Based on these values the two variants are characterized properly.

Table 2. Characteristic properties of machine variants with light and heavy spindle

	"Light version"	**"Heavy version"**
Configuration influenced Eigenfrequencies	5th: 56 Hz 6th: 57 Hz	5th: 49 Hz 6th: 52 Hz
Location of Centre of gravity of spindle unit	X: 0 m Y: 1.35 m Z: 1.74 m	X: 0 m Y: 1.40 m Z: 1.84 m
Cross-Talk EZŸ (static)	0.24 – 0.4 $\mu m/m/s^2$	2.2 – 3.6 $\mu m/m/s^2$

The analysis of these two variants leads to the conclusion that the machine with the light spindle unit should be preferred. Otherwise, the spindle unit's fixation point would have to be lowered, which automatically reduces the working space but runs counter to the initial constraint.

Generating the two models would generally last a few minutes, depending on how detailed the variants are. 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 module data. The calculation time for the two variants including the generation of the figures amounts to only some seconds each.

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 the can be based.

5 Conclusions and Outlook

The presented Axis Construction Kit provides reliable physical information on the behaviour of modelled machine structure variants. The structure itself is modelled as combination of different module models which are given in a module library. This efficient modelling and evalutation tool is used within the first phase of a configuration methodology for reconfigurable machine tools. The assessment of structural variants can be based on reliable data which increases the basis of relevant information for decisions at that early stage.

Since reconfigurable machine tools and their components, unlike conventional machine tools, cannot be optimized for the chosen configuration, an enhancement of the properties by the control system becomes relevant, even crucial. For this purpose, the data from the machine configuration file can be used to generate a control model being integrated for compensating dynamic and thermal effects. These models have to be generated automatically with the control parameter set and integrated into the control.

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