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Modeling Machine Tools and Load Dependency

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Abstract. The article will analyze the modeling of machine tools and their dependence on the load.

Keywords: machine, analyze, effects, dynamic, simulation, workpiece, graphical, VMP, NC, model, respective, positions.

Introduction

In this chapter a thorough approach to modeling machine tools will be given. The goalof this chapter is to derive a model which includes all major physical effects, but still can be created and solved efficiently. The previous chapter already introduced the software Virtual Machine Prototype, its features and its graphical user interface. In this chaptera detailed look at the methods and algorithms that are used by VMP to model machine tools is given. Therefore the general program flow will be described, before describing theprogram parts in detail.

In Fig.1 the layout of the simulation software Virtual Machine Prototype is presented. The software starts by reading a file that contains the NC path. This movement includes the acceleration, velocity and position for each axis, discretized at the IPO cycle (cycle of the NC's interpolator) of the controller.

The simulation software has three staggered parts, depending on the respective time scale of the problem. The range of these time scales is shown in Tab. 1. The dynamics of the machine tool, will be calculated at the IPO cycle, based on the movement. The thermal effects are slower and therefore larger time steps, will be used for the FEM simulation. This is necessary because of the higher complexity of the FEM simulation. The average time step for the FEM simulation is in the order of a few seconds.

Table 1.: Time scales of the simulation software

Dynamics	Thermal	Mechanical
ms	s	s–min

The software retrieves the movement which will be made in the next time step of the FEM simulation and calculates the loads on all machine elements using a multibody dynamics model of the machine tool (Fig. 1). The dynamic forces which act on the machine elements are calculated based on the accelerations given by the movement of the machine tool. Using the results from the multibody dynamics simulation, load dependent values of each machine element can be

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calculated. These for example include losses and heat conductivity in machine elements with rolling bodies. In order to calculate the losses, the velocities of each element are used.

All axis positions, losses, heat conductivities and so forth use the IPO cycle time. Be- cause of this, they will be averaged for the FEM time step and the FE model will be updated with all current values. After the thermal FEM simulation has finished, the displacement of the TCP can be evaluated by the mechanical FE model. However, as the update of the TCP displacement is not necessary at every time step, it will only be done periodically. The whole computational cycle is then repeated for the next time step of the FEM simulation.

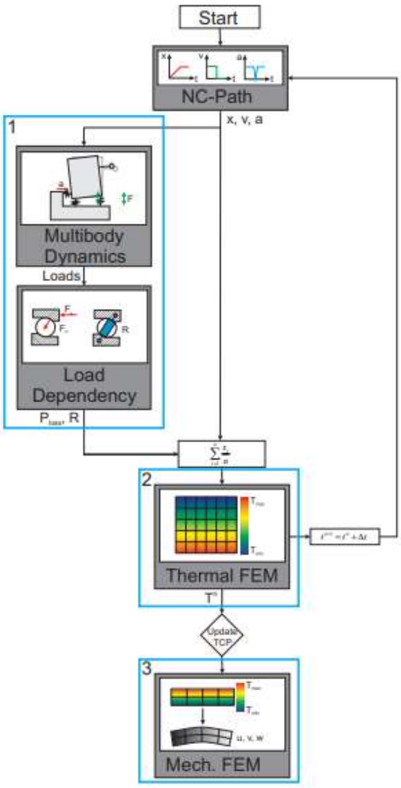

Figure 1: Layout of the simulation software

The first part of the simulation is that the NC-path for the next FEM simulation time step is read by the software. The time step, at which the acceleration, velocity and position are read, is made smaller and can be set to the IPO cycle time of the control system. The acceleration is then used to calculate the inertial load at each time step according to the acting accelerations. These loads on the coupling points will be used in Section 4.4 to calculate the load dependent friction. Given the velocity of the axis it is then possible to calculate the power loss together with the load dependent friction. The velocity is also necessary to calculate velocity dependent conditions, such as fluid film lubrication in the rolling bodies. The friction models resemble the well-known Stribeck curve in which dry, mixed and fluid friction are distinguished between, depending on the velocity of the friction partners.

The position of the axes is not used for the computation of the loads or losses. However it is necessary to update the position of the axes in the FE simulation model. For this the averaged position in every time step will be taken and the position of the individual axes will be updated. Based on the new position, the couplings between for example guideway and guide carriage will be updated, in order to integrate the power loss and heat conductivity of the coupling points at the appropriate axis position. This is shown in Fig. 2, where on the left side the coupling at location A is seen. On the right side the axis can be seen after a position change. The old couplings have to be disconnected, whilst the coupling at the new position is introduced.

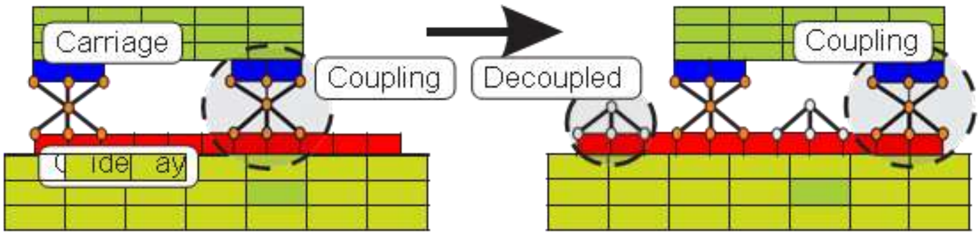

Figure 2: Change of position and appropriate coupling/decoupling of axes

Multibody dynamic models are often used to analyze the dynamic behavior of machine tools. In a multibody model the machine tool is made up of a series of rigid bodies con- nected by springs and dampers. Each rigid body corresponds to the structure of an axis slide, whilst the springs and dampers are used to model guides and drives. This leads to small systems of equations of the machine tools' dynamics (1.1) which can be solved in a very short amount of time, but still provide rather accurate results. Multibody dynamics can also be used to analyze the harmonic response and eigenfrequencies of a machine tool. The multibody dynamics model consists, of the following three parts: the masses and in- ertia of each rigid body, the springs which couple the bodies and the load acting on the bodies. As only a quasi-static analysis is performed, damping is not considered. These parts will now be described in more detail. The conversion from a FE model to a multi- body dynamics, with the above-mentioned parts, is shown in Fig.3. The most obvious difference is that in the multibody dynamics model there is no more spatial discretization of the bodies, as indicated by the FE mesh.

$$[M]\{\ddot{x}(t)\} + [D]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\} \quad (1.1)$$

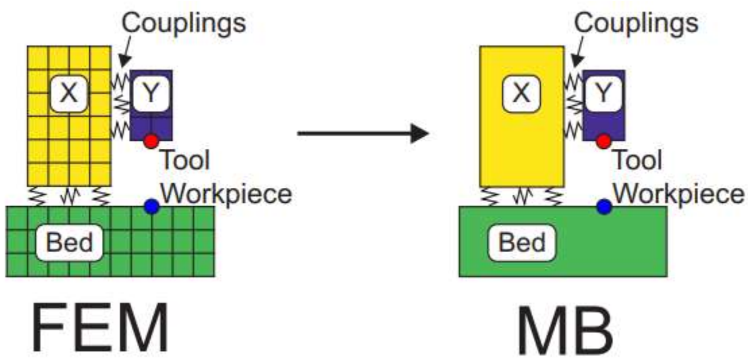

Figure 3: Conversion from a FE model to a multibody dynamics model

The computation of the load dependent effects in the machine elements consists of a series of steps. The first step is the computation of the load on each coupling point. As the multibody dynamics software does not yet consider frictional loads, these are added to the internal load at this point. The friction load of each machine elements has to be carried by the subsequent elements in the kinematic chain of the corresponding drive. In Fig. 4, a single linear axis is shown, for demonstration. In the gray circles the frictional forces from other components, that act as external loads on the selected part are shown.

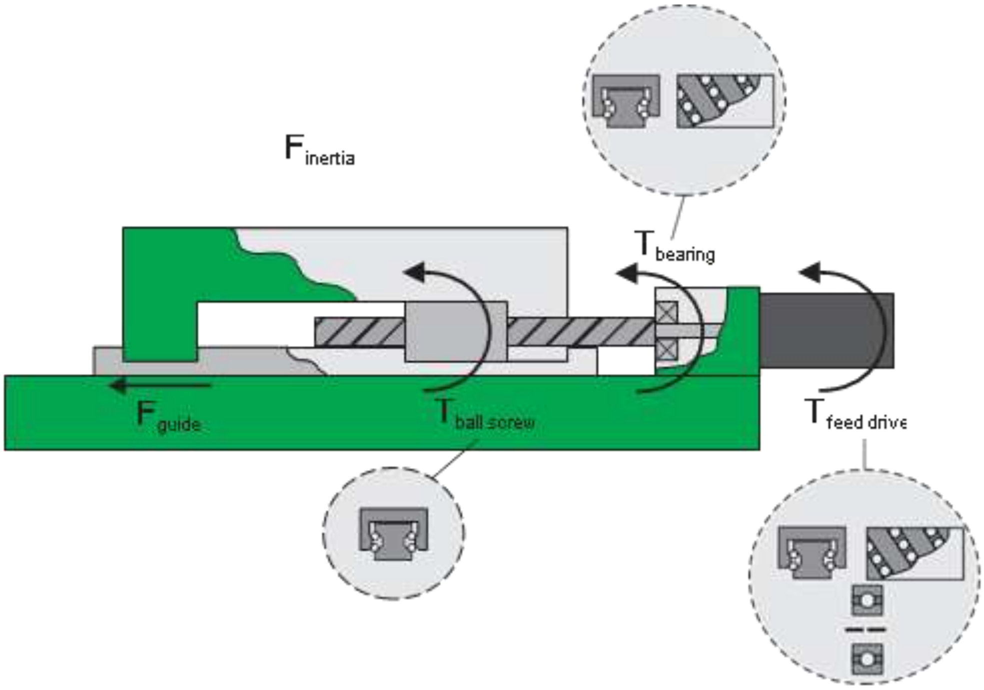

Figure 4: Components and their respective loads along an axis

The guide carriages have a friction force, relating to the load and velocity on the rolling bodies inside the carriage. The friction forces of all guide carriages, as well as the inertial load, then act on the ball screw. Progressing through the kinematic chain of the drive, each part has to bear the inertial load and the frictional force of the previous parts acting on it. In the end, the feed drive has to supply the whole torque acting on the axis.

A FEM model will be used to calculate the temperature distribution of the machine tools' structure. Again, as the structure is made up of multiple axes, some considerations on how to appropriately model the structure are needed. Similarly to the multibody model, where each axis is represented by a body, each axis is modeled using a separate FE model. This means that for each axis a mesh has to be created and then the appropriate boundary conditions have to be set. Setting meaningful boundary conditions is the most demanding part when simulating machine tools. In a common FEM analysis the designer has to assign a value for each boundary condition. However, values for heat conductivity and losses in bearings for example are not well-known and assumptions have to be made and to be validated by a sensitivity analysis.

In the following context a list of models exist for common machine elements. The designer has to supply the specification of the machine element and the corresponding model will automatically assign physically correct boundary conditions, based on the current load case. The list of models, which will be explained in detail later, includes the following machine elements:

- Guideways / guide carriages
- Ball screws / nuts
- Bearings
- Rotary axis
- Electrical drives: Feed drives and spindles
- Cooling devices

Besides these boundary conditions convection has to be applied on the free surfaces and the mechanical fixture has to be set at the bed.

Given the schematic of a machine tool in Fig. 5 it can be seen that the axis configu- ration, from tool to the workpiece, can be described as

t-X-b-w

where t stands for the tool, b for the bed and w for the work piece. This axis configu- ration has to be supplied to the software and for each axis the corresponding FE model will be imported. After the whole machine tool is assembled the necessary boundary con- ditions and machine tool components, for example guideways and ball screws need to be set. Especially guideways and ball screws are important as they act as coupling elements between the different axis parts.

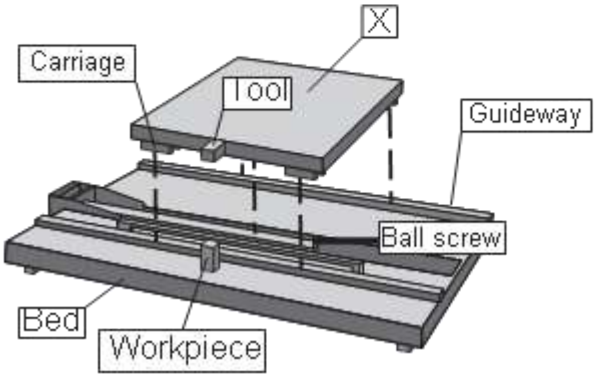

Figure 5: Schematic of a machine tool axis with its couplings between the bodies

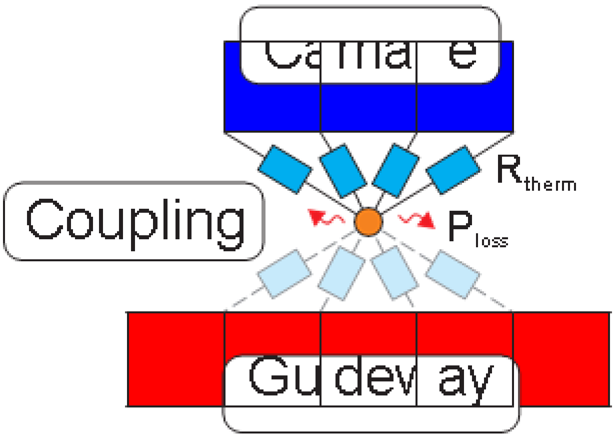

Figure 6: Thermal coupling between a guide carriage and guideway

For each guide carriage/ball nut a coupling node (see Fig. 6) is introduced into the system of equations. This coupling node, drawn in orange, acts as a bulk node to represent the rolling bodies, with all their thermal properties as heat capacity and conductivity. Due to the movement of an axis the part of the guideway/ball screw in contact with the balls will always change, indicated by the shaded areas in Fig. 6. Therefore it is necessary to determine the nodes in contact at each time step and update the thermal matrices with the new connections to implement the changed heat flow. For each coupling element a network of parallel heat conductivities, depending on the number of nodes in contact, has to be calculated. The total conductivity of this network corresponds to the resultant heat conductivity of the coupling element.

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