DESIGN OF A HOVER-AXIS FOR A HIGH-DYNAMIC MACHINE TOOL

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New demands on the structure of machine tools arise in the field of high speed cutting (HSC). Mainly the inertia properties reach an importance that they never had before. Thus, the concepts of how to build a suitable machine tool have to be thought over. Parts deflect under mechanical loads because of the finite stiffness of materials. When loads increase and the technical potential of lightweight design is used already only smart structures can increase the machining accuracy. The high dynamic machine tool, which is presented in this paper, offers this characteristic based on the magnetic guide in the z-axis. The magnetic guide not only guides the z-axis but also can be used as an actuator in the orthogonal directions. The aim of the research group „structure and control of high-dynamic machine tools" at the University of Hanover is to use this provided actuator for the compensation of deviations between workpiece and tool centre point. An extended use of engineering is necessary as for this application almost no construction guide lines are available. For this task ADAMS is used as the central software.

INTRODUCTION

High speed cutting machine tools have a high potential to reduce the expenditure for manufacturing time. The increase of production efficiency, which could be achieved because of advancements of cutting materials, tools and processes, allows or even demands high operating velocities for easy to machine materials to keep chip thickness at an optimal cross-sectional area. However, often such high operating velocities reduce the achievable accuracy of the machine tool. To fulfil the high demands on machining accuracies the view on the machine tool must take the complete system into account.

This is the aim of the research group „Structure and Control of High-dynamic Machine Tools" established at the University of Hanover which is financed by the German Research Foundation (Deutsche Forschungs-gemeinschaft DFG), figure 1. Basically, the main components of the concept for an un-conventional HSC machine tool are the linear direct drives and the linear magnetic guides. Magnetic bearings are highly developed for rotational tasks but their use as linear guides is up to know unusual in machine tools [Tie97]. The comparison to linear guides with ball retainer requires a competitive dynamic stiffness. On the one hand this claims a high-resolution sensor and on the other hand high calculation capacity for digital control tasks, that is also used for the linear direct drive. For this reason the real time operating system RTOS-UH was brought to a PowerPC with RISC-architecture.

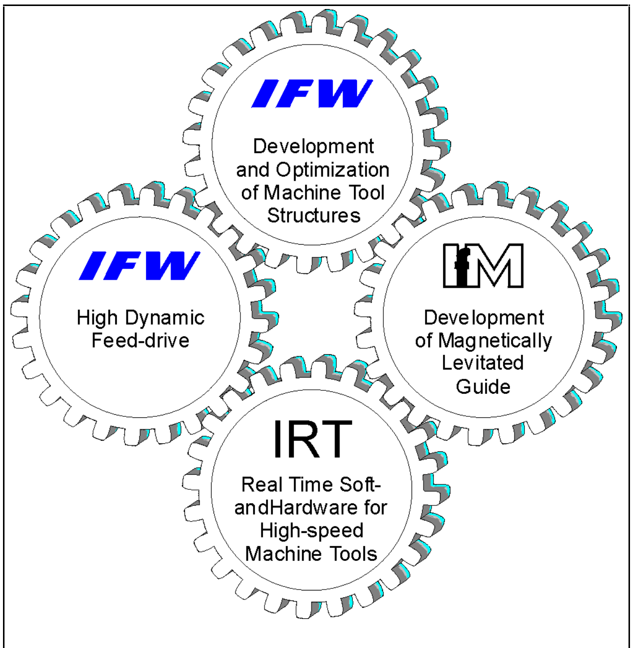

Figure. 1: research group „Structure and Control of High-dynamic Machine Tools" at the University of Hanover

THE HIGH-DYNAMIC MACHINE TOOL

The main requirement for the new finishing machine tool is the enormous acceleration of three times the acceleration due to gravity 3g which should be available in all axes. This requirement normally includes even high mechanical loads on the structural components such that they deflect to an extent as it is not allowed for a precise machining process. Moreover these loads represent a broadband excitation due to abrupt changes of the acceleration conditions. To avoid this broadband excitation machine tools in general have a limitation of jerk. This means that the rate of change for accelerations of the axes is limited. But the limitation of jerk extremely affects the potentials of high-dynamic axes [TöK99]. For this reason a completely new type of machine tool was designed within the research group, **figure 2**.

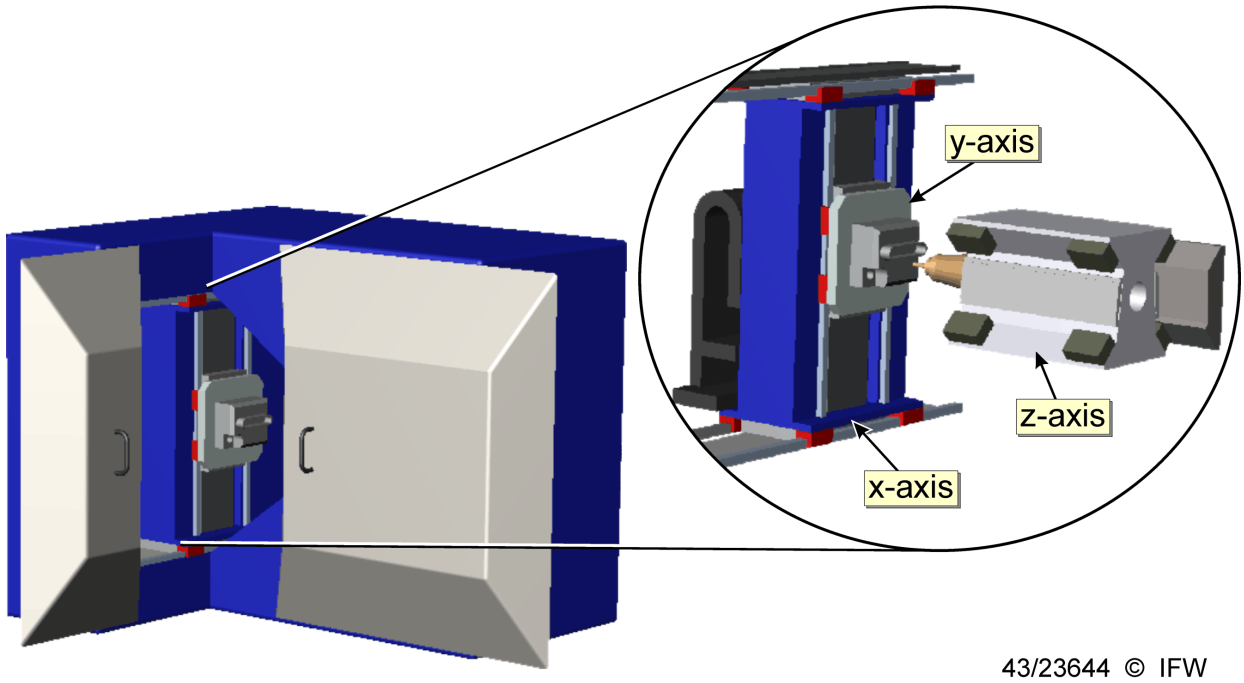

Figure 2: high-dynamic machine tool with accelerations of 3g in each axis

The basic structural components of the new concept for this unconventional machine tool are the linear direct drives and the linear magnetic guides. Whereas each axis is driven by the power of linear direct drives only the z-axis is guided magnetically. For this reason the most interesting machine part is this hover-axis without any mechanical contact to the frame. A multivariable control system, which makes use of a verified rigid body model of the structure, co-ordinates the action of the linear direct drives and the linear magnetic guide system as an orthogonal actuator. Thus, a system came into being whose characteristics are dominated by its mechatronic components linear magnetic guide and linear direct drive such that it is suitable for an advanced rigid body model in ADAMS, **figure 3**. To reach realistic simulation results the control strategies are performed in Matlab Simulink in which a model of the hover-axis is implemented.

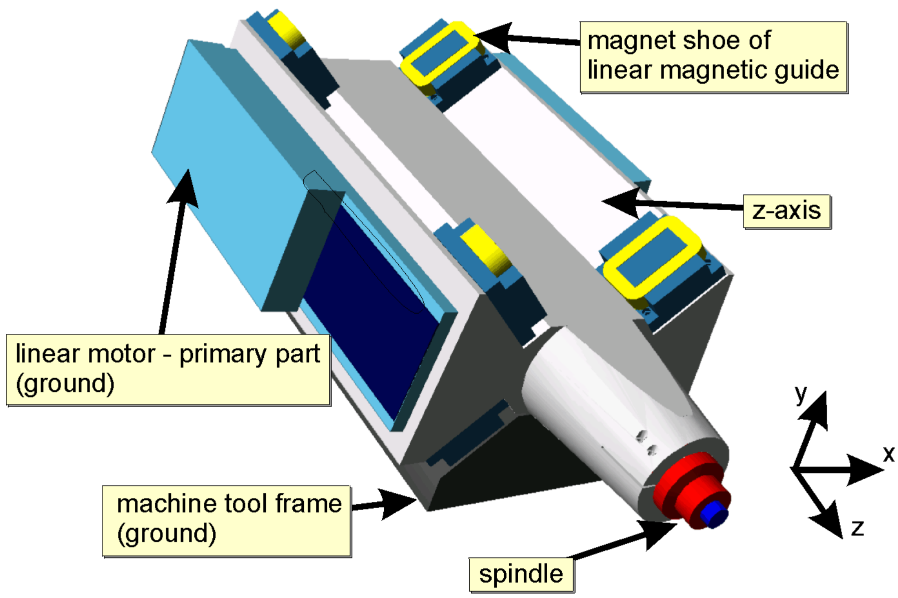

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Figure 3: ADAMS model of the hover-axis

The hover-axis is built up of several structural components which have to be taken into account, **figure 4**. Beneath the dominating linear direct drives and the linear magnetic bearings the basic body of the z-axis is also important even if this part is passive. But this does not mean that it can simply be modelled as a rigid body. On contrary in this circumference it will have to be modelled elastically as will be shown later on.

Another influence on the system is concerned to the spindle. On the one hand inner torques occur due to acceleration and deceleration of the spindle. On the other hand the rotating shaft represents a inertia characteristic regarded from the mathematical point of view. And last but not least there are process forces acting between the tool and the workpiece.

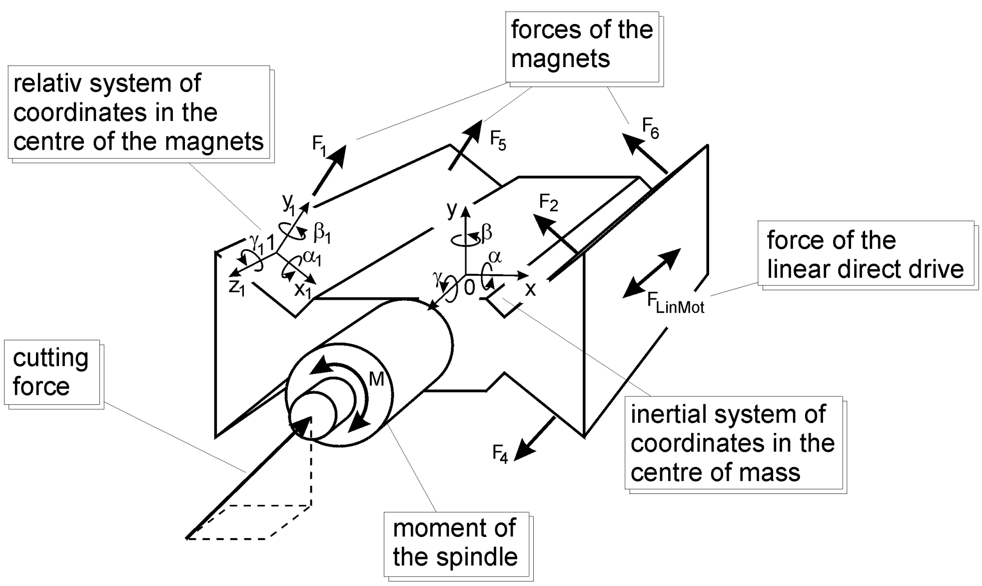

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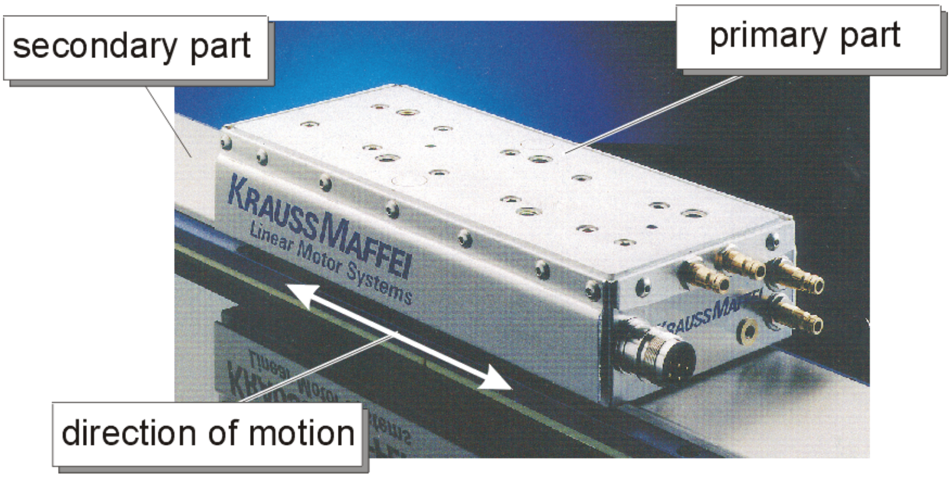
Figure 4: outer and inner physical effects to be modelled

LINEAR DIRECT DRIVE

Linear direct drives can be understood as rotational motors that were cut on one side and then were unwinded. Doing this one gets a primary and a secondary part of the motor and consequently the motor torque changes into a force that causes linear motions, **figure 5**. In machine tools these linear direct drives compete in general with recirculating ball screws. Whereas the latter is on the whole a mechanical system with elasticities the driving force of the linear direct drive acts directly on the machine tool axis. Due to this fact a quicker increase of the force is possible and thus higher dynamic characteristics are achievable.



source: KraussMaffei

Figure 5: structural component linear direct drive

For the z-axis of the high-dynamic machine tool two linear direct drives „LIMES TS 600/180-P12-1-0-VQ1“ of KraussMaffei are used. Its nominal force is 3.600 N and the maximal force is even 7.920 N. But they also have a huge force component that is in general unwanted but also inevitable. This is the permanent attractive force of 18.000 N between primary and secondary part. Due to this attractive force friction and wear in a normal guiding system significantly increase and especially in a magnetically levitated guide these forces would demand permanent reactive power. For this reason two linear direct drives are arranged in opposite to each other such that the forces compensate each other to a immense extent, **figure 6 a**.

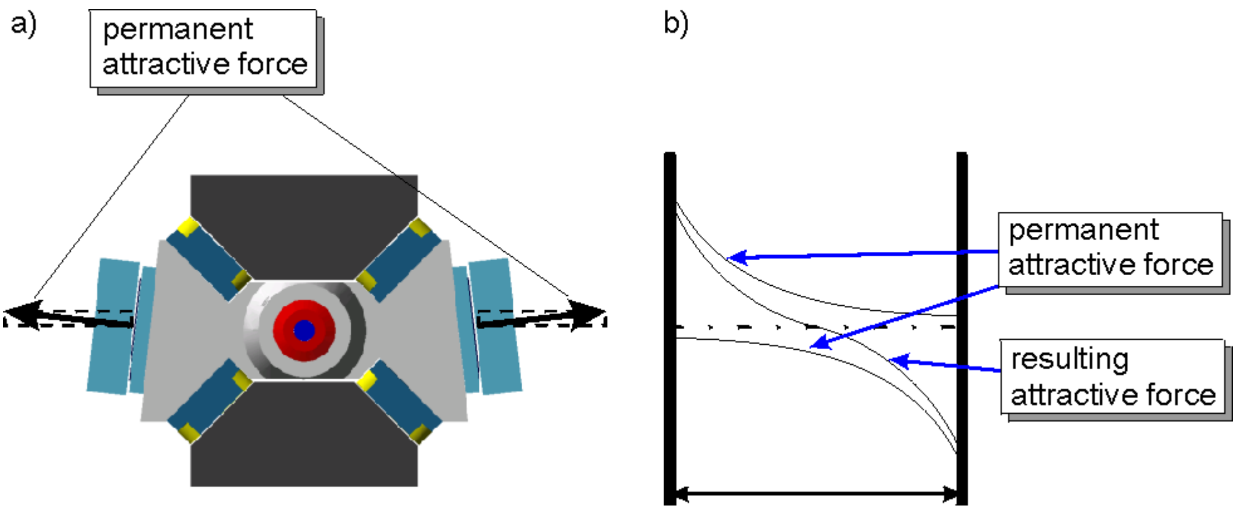


Figure 6: force compensation with two linear direct drives

The permanent attractive forces do not compensate completely as they are influenced by the air gap between primary and secondary part. These forces rise nearly hyperbolically with decreasing air gap and reach a maximum when the two parts stick together. The resulting force is shown in **figure 6 b**. When the z-axis is in its central position the forces eliminate each other but this is only a metastable condition. Moreover rotational deviations may occur as it is shown in **figure 7**. Just as the state for linear deviations this state is not stable as well. Because of the locally differing attractive forces a torque emerges that even increases the rotational deviation. To be able to model this effect in ADAMS the attractive force distributed over the plane is represented by six single forces that are arranged in a 2 by 3 pattern. The forces are fixed on the primary part and act corresponding to the physical phenomena correctly on the secondary one.

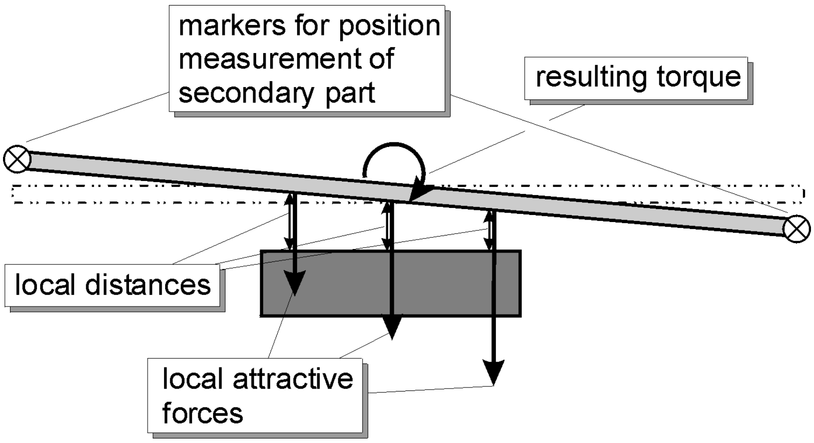


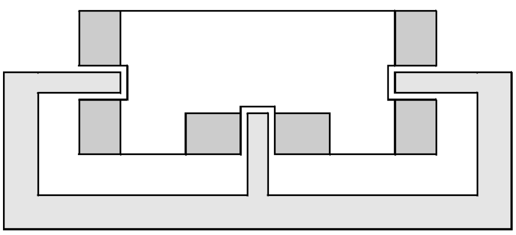
Figure 7: locally differing attractive forces and local distance calculation for the ADAMS model

The distances cannot be measured in ADAMS directly as the secondary part is movable. Therefore the deviations at the ends of the secondary part are measured by referencing them to the ground to be able to calculate any deviation between them. The measurement can be carried out referenced to the ground as long as the primary part is also defined as a part of the ground. In case of modelling the machine frame the measurement has to be changed.

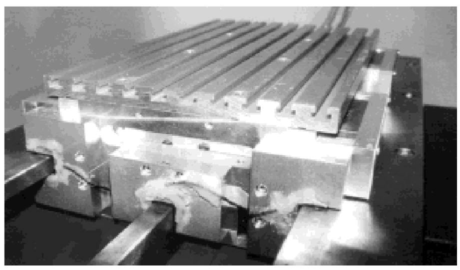
MAGNETICALLY LEVITATED GUIDE

Magnetically levitated guides are a new technology for the use in machine tools. But nevertheless a first design was realised within the research group, **figure 8**. This type of guide competes with linear guidance systems with recirculating linear ball bearings.

(a)



(b)



source: Institute of Mechanics, IfM

Figure 8: test stand for a magnetically levitated guide

Since a magnetically levitated guide without control is unstable its stiffness characteristics result mainly from the control strategy. Due to an integrating part a static load can be compensated completely. On the other hand dynamic loads cause bigger deviations as they do using conventional techniques. But it has to be taken into account, that the damping rate can be adjusted significantly higher as in mechanical components, **figure 9**.

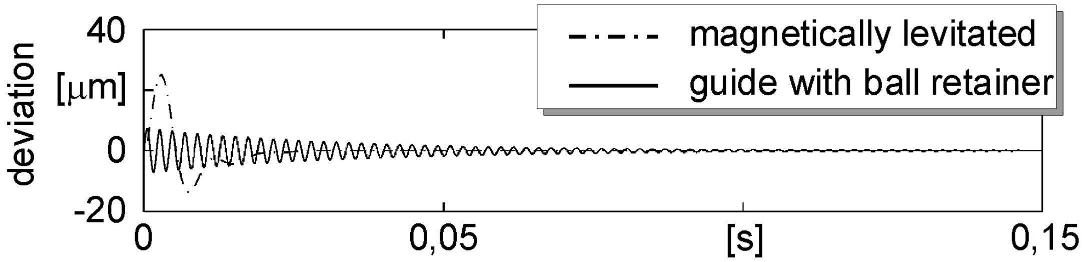


Figure 9: response on impact for mechanical and magnetically levitated guide [PoT99]

In the case of the presented machine tool eight single magnets, as it can be seen in **figure 3**, are used which are not designed as double magnets with „U"-shape. Consequently in a single bearing point only tractive forces can be applied, **figure 10**. This physical fact has to be taken into consideration when the Jacobean transformation is carried out. If the transformation reveals a demand for forces of pressure they have to be corrected. This can be done by handling the four magnets in the front and those in the back as a bundle and adding the same amount to all of them such that the forces of pressure get completely eliminated. The global effect still remains the same.

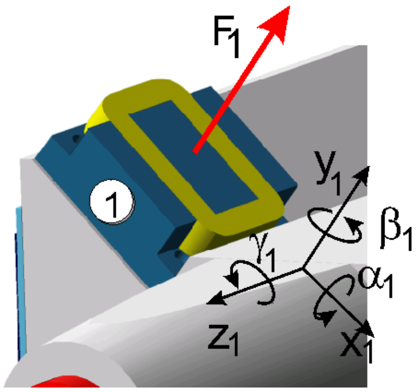
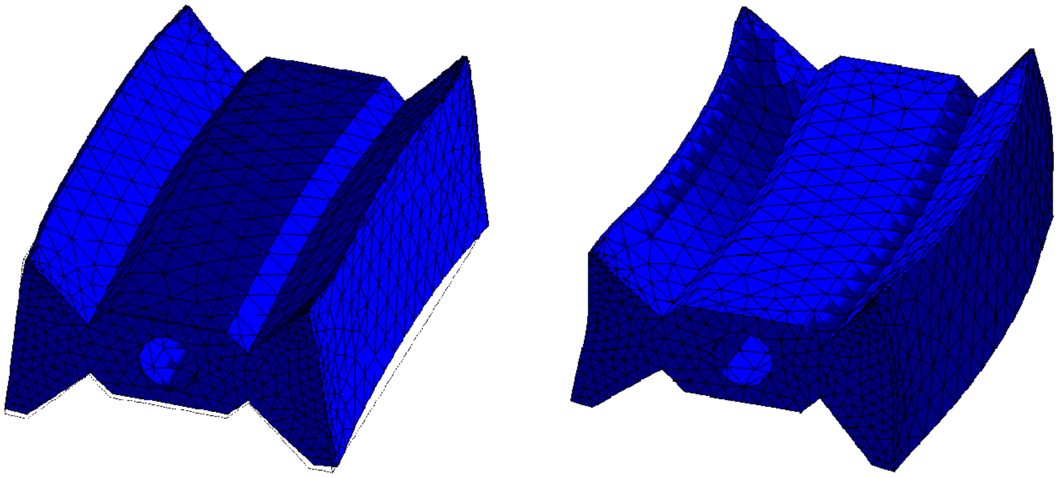


Figure 10: local measurement system and force at magnet 1

The necessary magnetic forces at each single magnet are calculated with a multivariable control system. For this task the deviations at the position of each magnet are measured and with an 8 x 5 - Jacobean matrix the five generalised degrees of freedom for the z-axis can be calculated. The correcting variables are calculated with a PID-similar, time-discrete multivariable control system. The necessary variables to control the single magnets are calculated with the mass matrix of the whole mechanical system and again with a 5 x 8 - Jacobean matrix to transform the general forces.

For the control task it is of high importance to know about the eigenmodes of the basic body. So far the control loop considers the z-axis as a rigid body construction neither with elasticities between the single structural components nor the components itself. But, as can be seen in **figure 11**, the bending modes of the basic body can lead to a misinterpretation of the actual vibration conditions. Both eigenmodes impose the system a rigid body movement because at all eight magnets the same deviation in the same direction can be measured.



bending mode around the x-axis of the machine-tool at 1012 Hz

bending mode around the y-axis of the machine-tool at 1045 Hz

Figure 11: eigenmodes imposing rigid body movements as a control input

Thus, the eigenmodes must be well-known to relieve their detection among the signals. When they are detected a special kind of high modal damping can be applied to damp this vibration mode and misleading interpretations can be avoided.

In the ADAMS model the deviations are measured against the ground because the guideways are considered to be rigid and to be fixed to the ground. If the machine frame comes into account then the same arguments become valid as already explained concerning the linear direct drive measurements. The forces are fixed on the magnets what is trivially to explain.

SPINDLE

The spindle is for sure not of the same importance for the whole system as the linear direct drive or the magnets, but it should not be neglected. The interest to model the spindle also is founded on two phenomena: first of all the spindle's torque is to be mentioned. But it may be estimated small. In second the spindle shaft rotates with speeds up to 60.000 rpm. The gyroscopic behaviour can become of importance when rotational vibrations occur, **figure 12**.

<u>important characteristic values:</u>

- speed n=60.000 rpm
- max. torque M=2,7 Nm

source: Fischer

Figure 12: spindle with inner torque and gyroscopic characteristic

The spindle is connected rigidly to the basic body of the z-axis. Only on the shaft acts a target value which is sent to a torque input without any use of a control. The exact rotation velocity is not of such high importance.

CUTTING FORCES

Machining forces should be neglectable in relation to the inertia, control, or feed forward forces. But they act via a lever as a torque and this may make it worth to have a closer look at them. Moreover these forces can be measured in experiments and then they can be used as realistic input and excitation for the ADAMS model, **figure 13**.

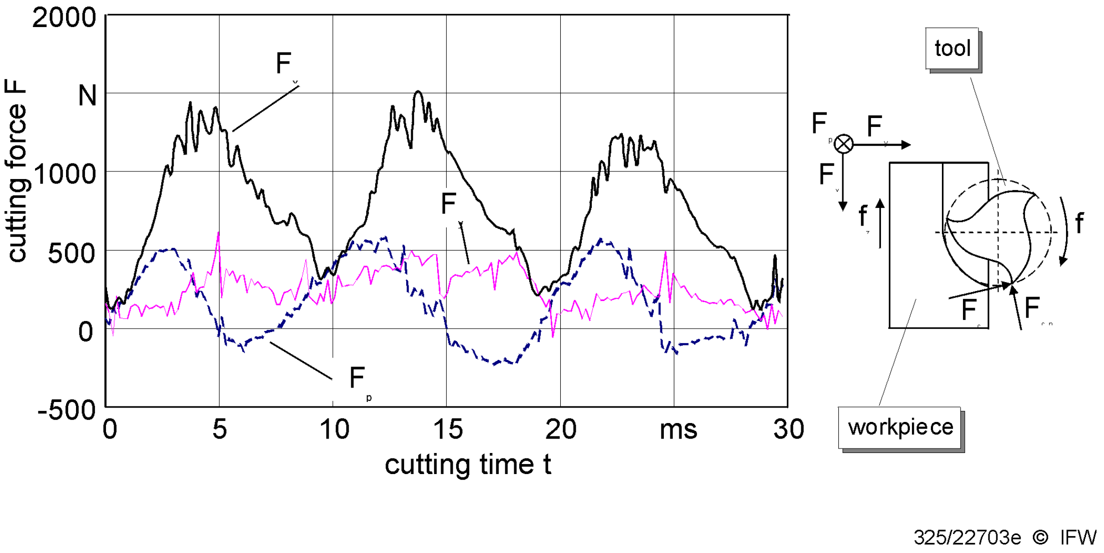


Figure 13: cutting force behaviour

SIMULATION RESULTS

With a reliable model various machining processes or movement conditions can be simulated. Of special interest are investigations how the structural behaviour varies with changes of constructive parameters in certain ranges.

Plausibility check

First of all some tests were performed as plausibility check. One test can be seen in **figure 14** were deviations are plotted. It can be seen that the magnetic guide is switched on in the start position. A deviation of the spindle box is needed to generate a first proper controller output to keep it in the right position. After 0.08 s the vibration dies.

Process simulation

Deputing for several simulations an investigation is graphed in **figure 15** in which the y-axis was accelerated harmonically with 2g and 10 Hz. Furthermore a machining force was supposed with a maximum of 1000 N at 20.000 rpm.

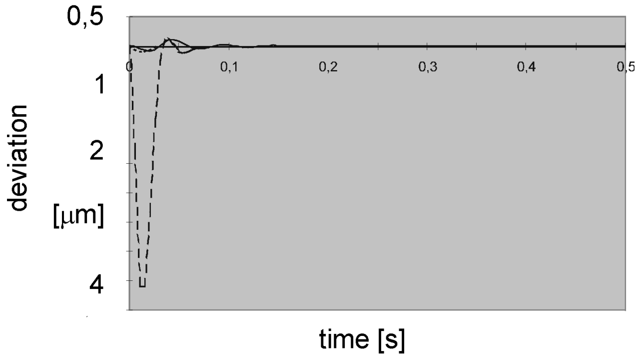


Figure 14: impact due to putting on the machine

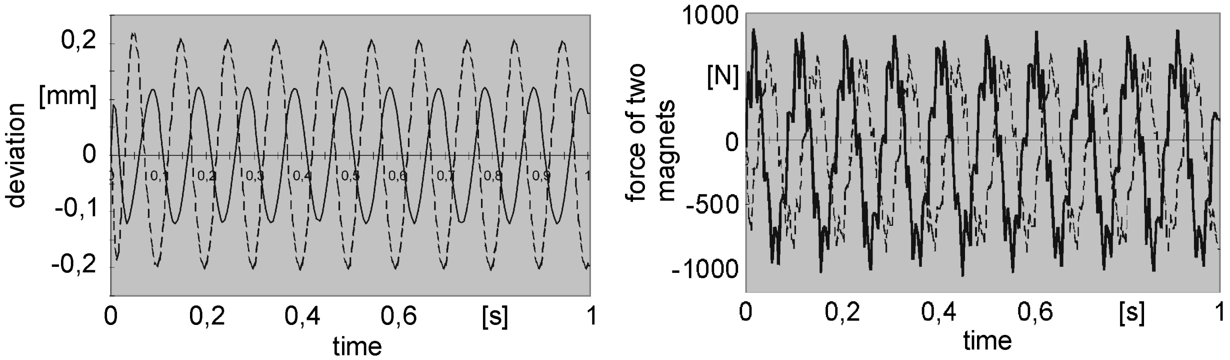


Figure 15: air gap changes at magnets and force response to a superposition of harmonic functions

CONCLUSION AND OUTLOOK

Based on this model the reaction due to accelerations of the axis or even due to process forces can be simulated. In this environment design studies are carried out for the structure and as well for control strategies. Furthermore the eigenforms calculated in ANSYS will be integrated in this model. By using the interface to ANSYS the flexible structural behaviour of the basic body within the rigid body system can be examined and predicted. Furthermore the simulation results will give an insight in the stress distribution which will be equalised by a topology optimisation to enable highest machining accuracies.

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