9. SYMPOSIUM "FERTIGUNGSGERECHTES KONSTRUIEREN"
SCHNAITTACH, 15. UND 16. OKTOBER 1998

MECHATRONIC DESIGN METHODS AND SOFTWARE IN MECHANICAL ENGINEERING

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ABSTRACT

The dynamic motion behaviour of complex mechanical structures can be improved by use of mechatronic design concepts and methods. Thus the mechanical parts of the mechatronic system are extended by actuators, sensors and modern digital online information processing systems. To determine and to optimize the functional dynamic features of the entire mechatronic system, geometrical, physical-topological, and mathematical models should be taken into account at an early stage in the design process before expensive test beds are used.

The realisation of such a model-based design process requires modern software systems. A tool coupling between the mechatronic development system CAMeL (Computer-Aided Mechatronics Laboratory, MLaP) and the commercial CAD/CAE/CAM system I-DEAS accelerates and simplifies the design process especially for design engineers who working visually. The automatic determination of dynamic models and analysis results (CAMeL) from the geometric models (I-DEAS) is supported by solution elements like bearings, gears, etc. The data structures of the solution elements describe the geometric and all physical properties which are usually required for the design of a mechanical system. In order to prove the advantages offered by the software tools employed and the solution-element objects, we will present the process of modelling a milling machine.

INTRODUCTION

The dynamic motion behaviour of complex mechanical structures can be improved by use of mechatronic design concepts and methods. Thus the mechanical parts of the mechatronic system are extended by actuators, sensors and modern digital online information processing systems. To determine and to optimize the functional features of the entire mechatronic system as well as the constructive layout, geometrical, physical-topological, and mathematical system models should be taken into account at an early stage in the design process before expensive test beds are mounted.

To achieve optimal design results many a realistic system model of the mechatonic products has to be assembled, modified, analysed, and assessed in an iterative optimization process. To speed up this design process, a fast and efficient determination of dynamic models and analysis results (e.g., simulation data, frequency response) on the basis of the constructive layout is an indispensable condition (Wittler, 1995). In the following, we want to present a solution to simplify and accelerate the design process of mechanical parts of a mechatronic systems especially for design engineers working in a visual manner. As an example, the design process of a milling machine will demonstrate the use of mechatronic design methods and modern software tools.

MECHATRONIC DESIGN PROCESS

For a software-independent modelling of the mechatronic design process, the objects of this process are structured and classified into model- and process-objects. The active process objects design and create the passive model objects. The passive model objects describe the different properties of the mechatronic system and can be classified into system models, analysis models (e.g., time-domain simulation), requirement models (e.g., maximum mass) etc. (Hahn, 1996). Furthermore, the system models can be classified into geometrical, physical-topological, and mathematical ones.

The entire design process is subdivided into hierarchically structured processes. The mechatronic design process starts with the design process of the kinematic, the dynamic and the mechatronic function (Lückel, 1997). These three processes lay out the essential properties of the dynamic system behaviour. On the basis of the kinematic and dynamic system models created in these processes, detailed geometric system models are created and optimized in the subsequent design process. Usually the dynamic system models have to be derived from the geometric shape in an iterative optimization process. This leads to the process structure displayed in Figure 1 (left).

On the basis of a geometric system model, physical-topological system models have to be derived in a first model transformation process which will be described in detail in the following. Here we want to demonstrate the determination of MBS models (Multi-Body System Models) from geometric models based on predefined solution-element objects. This transformation process is realized by a tool coupling between CAMeL and I-DEAS. In the second model transformation, process the mathematical equations are usually computed in explicit non-linear state-space representation form by discipline-specific formalisms (e.g., in mechanics by a Lagrange formalism). Undefined system parameters of the entire dynamic model and especially controller parameters (steering and feedback) have to be derived by means of methods from control theory (e.g., numerical parameter optimization, pole placement). For the assessment of the functional behaviour, analysis models (e.g., time-domain data) are generally derived via an analysis process (e.g., time-domain analysis process). On the basis of the analysis results experienced, engineers will have to decide whether and which modifications have to be made in the next iteration step (e.g., state-space controller instead of PID controller, modification of the geometric model, etc.).

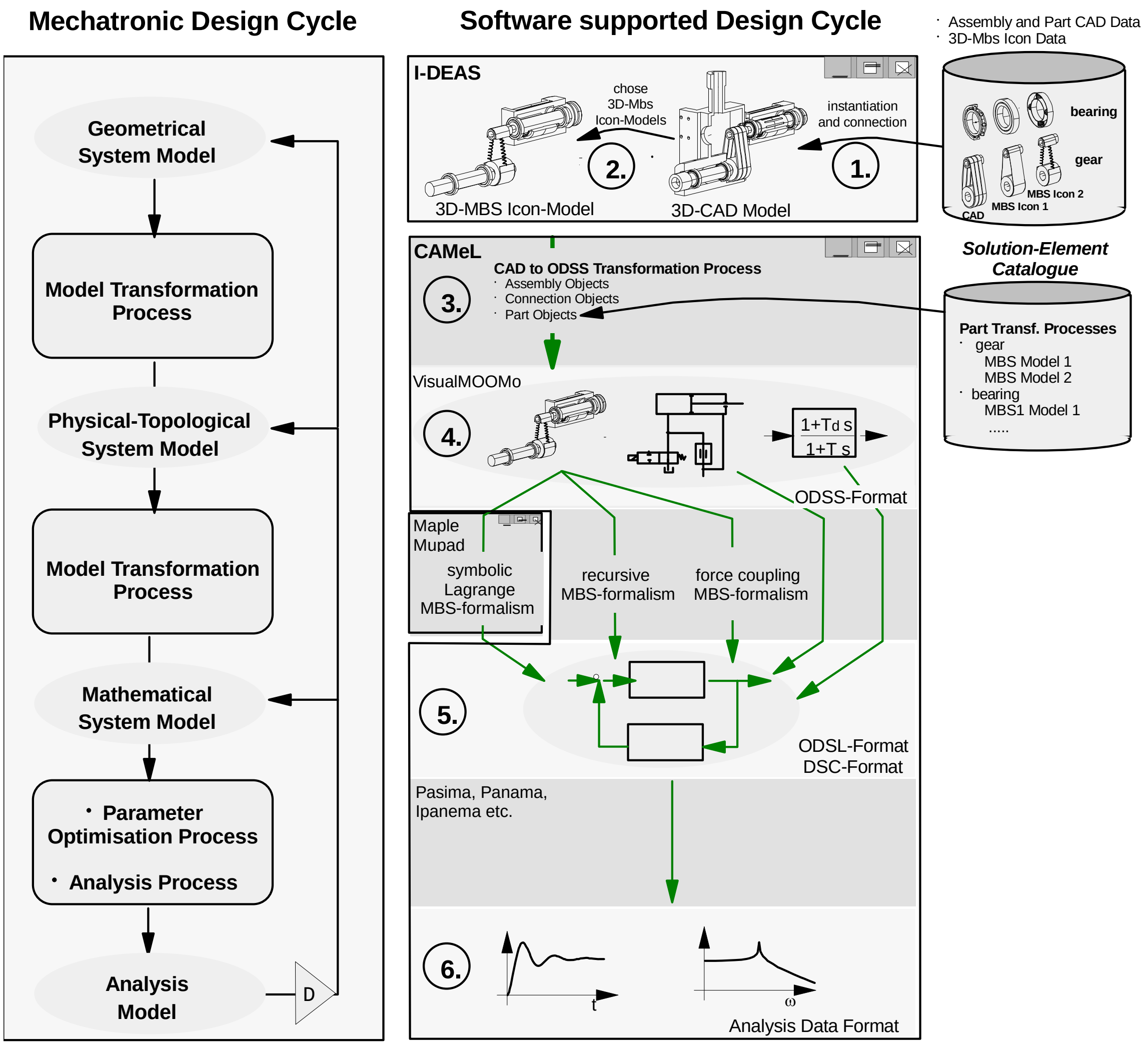

Figure 1: Mechatronic design cycle

SOLUTION-ELEMENT OBJECTS

There are different ways to determine physical-topological mechanical system models from geometric models, e.g., finite-element nets (van-Phai Nguyen, 1979) and also mass and inertia properties of single parts (Braid, 1974) can be derived by means of complex algorithms based on generally defined three-dimensional geometric models. These features are available in many modern CAD systems (e.g., I-DEAS). This kind of modelling leads to theoretical models usually without any feedback from the real system behaviour. Many of the properties of an MBS model (e.g., nonlinear gear stiffness, Coulomb friction) have to be determined by a large-scale identification (Schütte, 1995) and testing processes or other detailed and complex modelling procedures. Usually in this context, simplified interactions between the mechanical model (structure and parameters) and various effects, such as temperature, time, load cycles, and especially the geometric shape etc., will be determined.

As suitable and realistic models are vital in achieving accurate analysis results of the functional dynamic behaviour at an early stage in the design process, the knowledge of the dynamic behaviour of single components has to be preserved in view of future design processes. Also the supplier of components (e.g., gear, drive systems) will have to possess this knowledge which can now in part be obtained from catalogues. Even if realistic mechanical models can be determined without an identification process (e.g., thin and long elastic beams -> linear beam theory), the experiences in a sensible modelling of reduced MBS models should also be described and preserved.

There is no limit to possibilities of generating a physical-topological mechanical system model from a given geometric system model. Thus the mechanical models, among others, can be subdivided into discrete (e.g., multibody systems) or continuous (e.g., FEM finite-element method) models. Furthermore, the models also differ in the number of degrees of freedom, the model structure, the model parameters, etc. The selection of a suitable modelling depth for an MBS model requires a lot of experience and varies in the different phases of the design process. All this motivates the definition of predefined solution-element objects which will be described in the following.

Part Solution-Elements

A part-solution model object describes the detailed geometric shape and the functional dynamic behaviour of a single part by physical-topological MBS models. As the mathematical system models (e.g., mechanical equations of motion) of mechanical parts can only be derived from assembled entire systems, the mathematical model of a physical-topological MBS model is not included in the part-solution-element object. Thus the part-solution-element object consists of one three-dimensional geometric model and several carefully chosen, reduced physical-topological MBS system models. The undirected interaction between the geometric model and an MBS model is described by a transformation process. A sensible selection of the reduced MBS models and the definition of the transformation process have to be done by experienced engineers. In special cases the transformation process may be independent from the geometric model data.

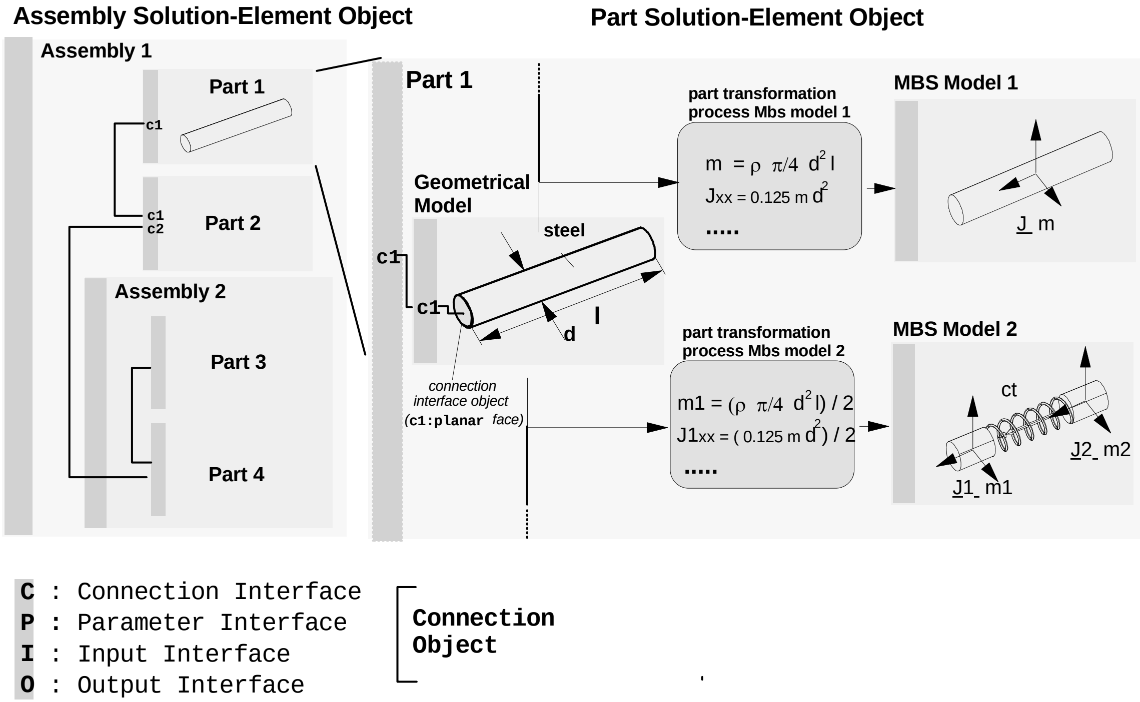

Figure 2: Structure of part- and assembly-solution objects

The three-dimensional geometric system model (Mortenson, 1985) of a solution-element consists of basic objects, such as points, lines, circle arcs, curves, surfaces, etc. Geometric (e.g., surface 1 parallel to surface 2) and parametric constraints (distance line 1 to line 2) define the pair-by-pair cohesion between these basic objects. The creation process of complex geometric models (e.g., rotate curve about line, cut body 1 and body 2) is usually also described and preserved. The three-dimensional physical-topologic MBS models (Haug, 1989) consist of elastic and rigid body, discrete spring and damper objects, etc. Idealized torsion and translation joint objects (e.g., no run out) define the pair-by-pair connection between rigid bodies. Furthermore, three-dimensional MBS icon models allow the design engineer to have a graphic impression of the MBS models. Such an icon model is only a graphical representation and does not contain explicit data about the MBS model.

Assembly Solution-Elements

During the iterative design process, models of single parts (e.g., spindle) and assemblies (e.g., controlled servo mechanism) have to be connected, disconnected and exchanged in the current system model. To support the process of modelling complex systems it is indispensable to arrange the component models according to the hierarchical part- and assembly-structure. Therefore assembly-solution objects are needed; they consist of part-, subassembly-, and connection-objects. The part-solution objects have already been described. The connection objects define the pair-by-pair connection between two different part-solution-elements.

A connection-, a parameter-, an input- and an output-interface allow the user to make defined modifications and interactions of the modular part- and the assembly-solution objects. The connection interface defines the geometric basic objects (e.g., faces, lines, points) of a solution-element which can be combined with other solution-elements by a connecting object (e.g., face-to-face, line-to-line). The parameter interface allows discontinuous and continuous parameter modifications especially of the geometric model (e.g., diameter of bearing) of a solution element. Also mechanical input (e.g., forces, torques) and output (e.g., velocity) vectors can be defined. The geometric as well as the physical-topological system models of the part-solution objects have also to fulfil the above-described requirements of the modular and hierarchical model data structure.

Model Transformation Process

The entire transformation process of a newly created assembly-solution-object is subdivided into the transformation process of the assembly-, the part-, and the connection-objects. The transformation processes of the part-solution objects are already defined. If more than one predefined transformation process is available, the design engineer has to choose a sensible MBS model. The connection objects result in MBS joint objects between two rigid bodies depending on the defined relative degrees of freedom. The transformation process of the assembly-solution objects can be seen as nearly a one-by-one process, because assembly objects describe the topology of the entire system model.

REALIZATION OF THE SOLUTION-ELEMENT-OBJECTS

The mechatronic design cycle and its software-based realization are displayed in Figure 1. The CAD/CAE/CAM system I-DEAS particularly supports the fast and efficient graphical construction and modification of new three-dimensional mechanical components, such as assembly solution-element objects based on a given part- and assembly solution-element catalogue. The mechatronic development system CAMeL supports the physical modeling and the analysis and optimization of the dynamic system behaviour of the entire mechatronic system model.

For a general implementation of the solution-element objects presented, the model data structure and the processes have basically to be extended and modified in CAMeL and I-DEAS. CAMeL is an open development system (Rutz, 1995) and is completely developed at MLaP. The commercial software system I-DEAS is not meant to be extended by external software developers. Thus a prototypical realization applied with an attractive example (milling machine) will prove the advantage of this idea. Its realization, the use of the solution-element objets, and also the software tools will be expounded in the following chapter.

MECHATRONIC DESIGN CYCLE OF A MILLING MACHINE

This chapter deals with a single design cycle (see Figure 1) at an early stage in the entire design process of a milling machine. On the basis of a given kinematic structure, a first 3-D draft model of the main spindle is constructed with the help of I-DEAS. Simplified, reduced dynamic models of the entire mechatronic system have to be derived, analyzed, and optimized with CAMeL. This process brings about preliminary, roughly sketched demands for the refining of the single components in the following iteration steps.

1st step - At first the user selects the required solution-element objects from the given solution-element catalogue (e.g., gear, bearing, cylindrical spindle element, see Figure 1) in a new assembly (I-DEAS assembly task). The geometric models of the solution-element objects are connected by line-to-line or face-to-face connection objects. Here the user is asked by the program which directions of the freedom of movement have to be suppressed between the connected tow parts. This leads the design engineer who works in a visual manner to a 3D-CAD model of the entire main spindle.

The internal topological structure of this newly created assembly solution-element “spindle drive” object is in part shown in Figure 3. The constructed “spindle drive” is also a subassembly of the entire “milling machine”. In this way, complex models of mechatronic systems can be made up from simple part-solution-elements. The spindle drive and the feed drive are both speed-controlled. The milling process module describes the dynamic behaviour and the generation of the milling forces (see Tlusty, 1991).

2nd step - In the next step one MBS icon model of every part solution-element object has to be chosen. The resulting 3-D MBS icon model of the entire system yields the user graphical and textual information on the features of the selected MBS models (e.g., mechanical degrees of freedom). In the following step, the user starts an automatic one-way data transfer from I-DEAS to CAMeL. Information on the assembly-, the part- and also the connection-objects of the visualized assembly solution-element object are exported (e.g., hierarchical structure, geometric parameters, the name of MBS icon models, etc.).

3rd step - On the basis of these geometric model data the ODSS (Objective Description Structure) description language format of the chosen MBS model is automatically derived in CAMeL. The transformation processes of the part-solution-element objects have already been implemented for the elements of the catalogue which are identified by the name of the selected MBS icon model. The transformation process of the assembly-, the subassembly- and the connection objects is completely done on the basis of the exported I-DEAS data.

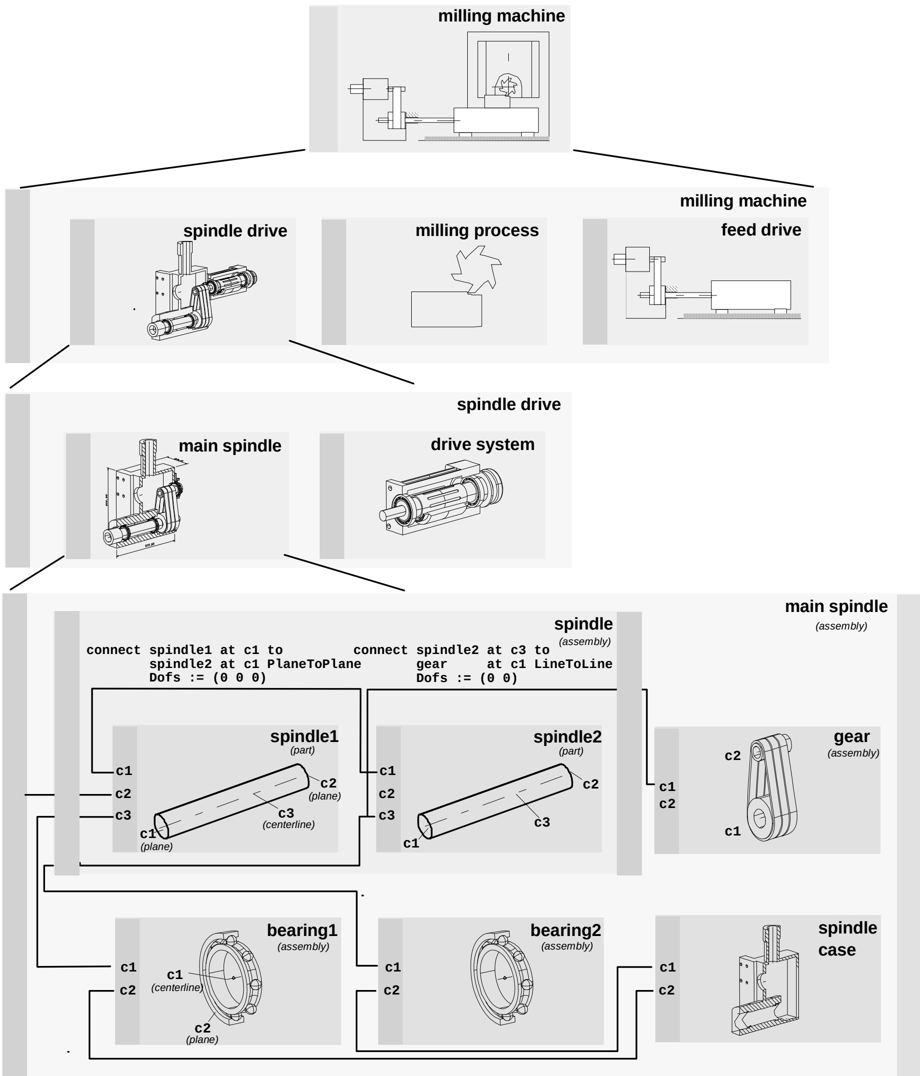

Figure 3 - Topological structure of the assembly solution-element object “milling machine”

4th step - ODSS is an object-oriented description language (Hahn, 1996) for the modelling of modularly and hierarchically structured physical-topologic models of mechatronic systems which consist of mechanical, hydraulic, and controller components. By means of a graphical CAMeL editor (VisualMOOMo, see also Naumann, 1996) the mechanical model is extended by actuator, sensor, and controller models. The CAMeL data-base contains many well-known and identified sensor and actuator models and also parameterised controller structures (e.g., PID controller, state-space observer).

5th step - In the next step the modular-hierarchical, parameterised non-linear state-space model of the entire mechatronic system is derived automatically in the ODSL format (Objective Dynamic System Language), but also in DSC (Dynamic System Code) and C code

(Richert, 1994). A symbolic Lagrange (Schütte, 1997), a recursive (Junker, 1997) and a force-coupling MBS formalism (Hahn, 1995) support the determination of the state-space models of the mechanical components. A very interesting feature allows to combine these three different formalisms. By means of the ODSS description elements, the entire MBS can be separated for the different formalisms with respect to their characteristic features. The partitioned mechanical substructures are automatically detected and connected in the ODSL structure. Thus substructures can for instance be prepared and portioned for a fast real-time simulation on distributed hardware platforms (Stolpe, 1997). Tools for the parameter optimization of linear and non-linear systems with vector-optimization criteria are integrated in CAMeL.

The generated entire model of the milling machine consists of 5 rigid bodies and 5 discrete springs. The MBS model is described by 7 generalized mechanical coordinates. The topology of this system comprises 4 closed loops which are automatically detected and closed by force-coupling elements. The rotational degrees of freedom are assumed to be small, which leads to an efficient simulation code by way of the Lagrange MBS formalism. The feed and the spindle drive are controlled by a conventional PI velocity controller. In parallel to the feed drive bearing, actuators are integrated (figure 4, see also Hagemeister, 1997). The velocities are fed back by a P-controller. This leads to a simplified active vibration damping of the mechanical structure. In this first step the controller parameters are determined by means of conventional control theory methods (e.g., pole placement).

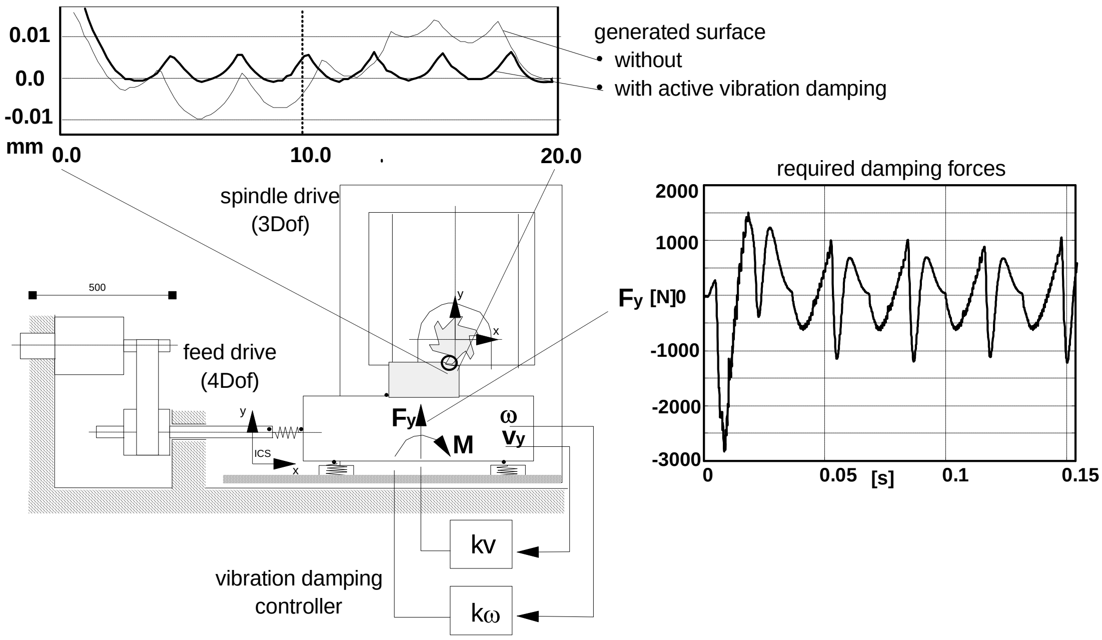

Figure 4: First simulation results of the milling machine

The models of the milling process are based on Montgomery (Montgomery, 1991). The milling forces depend mainly of the cutting area between the chip and the milling tool. In dependence of the states of the dynamic models of the feed and the spindle drive, this cutting area is calculated by a simple planar geometric model of the milling process at every simulation step. The surface of the working piece is described by 500 single points. These points are moved when the milling tool cuts the surface of the workpiece. On the basis of the computed cutting area, the cutting forces of each tooth are calculated according to well-known simplified force laws. The calculated forces are fed back to the dynamic models of the spindle and the feed drive.

6th step - As a result of a time-domain simulation process, the generated surface of the working piece is shown in Figure 4, with and without the simplified active vibration damping system. The required performance of the actuators of the active vibration damping system can for instance be determined by means of such simulation results. Based on these simulation results the design engineer will have to modify the system models in the following iteration step.

CONCLUSIONS

The development of modern and innovative machines requires mechatronic design concepts and suitable software tools. The design of the mechanical parts of a mechatronic system is elaborated by engineers working in a visual manner and supported by modern CAD systems. The determination of reduced mechanical MBS models for the layout of the dynamic system behaviour on the basis of CAD constructions requires a lot of experience in engineering. Realistic modelling of many mechanical components needs a feedback from the real system behaviour. All these information have to be preserved by the software systems in order to simplify and accelerate the modelling process of complex mechatronic systems. This paper presents a concept and an implementation (CAMeL, I-DEAS) to lay down these information by means of predefined solution-element objects. These objects describe the geometric and also the functional dynamic behaviour of well-known and identified mechanical parts and components. The modular data structure allows defined modifications of the properties of the solution-element objects. Reuse and an easy exchange of solution-element objects are supported by connection and assembly objects. The modelling depth of the entire system can quite easily be modified by selecting a useful MBS model of every part solution-element. This is a very important feature which is required in the different phases of the mechatronic design process. The advantage and suitability of this idea are shown by an attractive example. The development of modern software systems for the design process of mechatronic systems is an important research activity at MLaP. There are many possibilities to extend these research activities in the future. Other disciplines (e.g., hydraulics) can for instance be included in the solution-element objects. The general structuring and the coupling of different CAx software tools and models pose many as yet unanswered questions. A continuous modelling process over all the stages of the mechatronic design process has also not yet been realized.

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