Object-Oriented Modelling for Energy-efficient Production

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Abstract. Energy optimization in production plants is at present a very current topic. In this context, the research project INFO deals with a comprehensive simulation of production halls with all micro- and macrostructures, in order to be able to make qualified predictions about the efficiency of different energy saving measures. An important sub-range of this research concerns modelling and simulation of machine tools, two parts of which will be presented in this article.

The first part focuses on general multi-domain modelling of an actual machine tool. An object-oriented modelling approach allows combining electrical, mechanical as well as thermal aspects in a structural manner. Combined top-down and bottom-up modelling techniques with increasing level of detail identify the degree of modelling effort necessary or sufficient for certain applications and simulating certain scenarios. Future work plans to validate the simulation results against measurement data obtained from machine tests with the lathe.

The second part concentrates on the thermal coupling of the machine tool components with the environment. For that we selected a specific area of a machine tool, i.e. a linear guiding device with drive motor. In a first step the thermal behavior is studied and in a further step we consider the heat transfer and other effects on the environment. For this, the room around these tools is discretised in thermal compartments, which can also affect each other. The object-oriented modelling approach allows refining the discretisation easily, so that effects of a higher resolution can be studied too.

Introduction

The research project INFO (supported by the Austrian Research Promotion Agency (FFG)) [1] pursues the primary goal to increase energy efficiency in production plants by considering various disciplines of energy technology, production technology and building design in a comprehensive approach [2]. Qualified and customized predictions and recommendations about the efficiency of different energy saving measures can be made using comprehensive simulation models of the production plant including all relevant micro- and macro-structures and therefore identify potential savings in manufacturing plants.

Due to the size of the project and the various aspects that are considered, the project is highly interdisciplinary. This makes it necessary to gather experts from many different fields, e.g. engineering, thermodynamics or building simulation, who build the models specific for their field of research using specific approaches and spezialized simulation tools. The different partial models are then combined to an overall simulation.

One interesting topic in the context of the project is to look at machine tools from an energetic point of view including power consumption and heat emission [3]. There are two main reasons this topic is interesting with regard to a comprehensive simulation:

First, the size of the resulting model makes it necessary to study the level of detail in which the individual parts can be modelled and if it makes sense to have partial models in a very high resolution. Therefor the first part of this study deals with multi-domain simulation model of a machine tool that is modelled in three levels of deatail and analysed regarding simulation time and numerical stability.

Second, the behaviour and the time scales of the models are very different, so it is essential to study the possibilities on how to couple the different model parts. To analyse the problems that occur because of these aspects a part of a machine tool, a linear guiding device, and a room model are considered for the second part of

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this study. In order to consider only effects that occur due to the coupling of the two model parts, the partial models themselves are kept on a rather low level of detail.

The new object-oriented modelling approach applied in both parts of this study (called Physical Modelling) is designed for modelling and simulation of physical systems in various domains and has proven its worth over the last years. Not only does this approach make the modelling process simpler, faster and more intuative, the models are also more modular allowing the user to easily refine the structure by adding new components in a structural manner.

Since there are a number of software tools available for Physical Modelling in multi-domain applications, choosing two different tools for our implementations (i.e. MATLAB / Simscape™ [4] and MapleSim [7] in our case) allow comparisons regarding numerical performance, suitability and usage.

1 Multi-Domain Modelling of a Turning Lathe

In our study of modeling and simulation of machine tools, we consider not only electric drive components and mechanical elements, but we are also interested in the waste heat developing in different places. In order to be able to validate the model against actual measurement data, we attempt to recreate an actual turning lathe, which is provided by the Institute for Production Engineering and Laser Technology from the Vienna University of Technology. Although the considered machine tool is rather simple compared to others, it provides sufficient possibilities for our investigations. There are three main drivelines:

- Main drive: Main motor, gear belt drive, spindle with chuck and workpiece
- Longitudinal feed (z-axis): Servomotor, leadscrew drive and slide holding the cross feed
- Cross feed (x-axis): Servomotor, leadscrew drive, cross-slide with tool holder and cutting tool

The main drive sets the workpiece into rotation, longitudinal and cross feed drives allow positioning the tool in z- and x-direction (axial and radial to the workpiece), see Figure 1 During machining, the cutting tool penetrates the workpiece and removes material in form of a chip during relative motion.

The cutting energy is mostly converted into thermal energy. All three drivelines receive their electric power from an inverter, which is simplified as ideal voltage source.

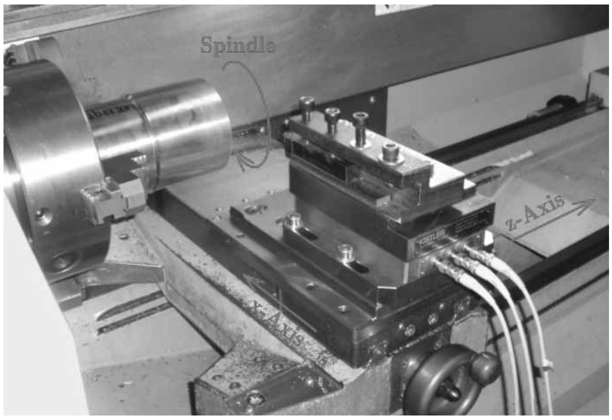

Figure 1. The three axes of the lathe: Spindle for driving the workpiece, longitudinal and cross feed for positioning the tool in the z- and x-direction.

The model is implemented step by step with gradually increasing level of detail allowing to identify numerical boundaries of our simulation. On the other hand we can also show what degree of modelling effort is necessary or sufficient for certain applications, where significant changes in the simulation results are to be seen and which simulation scenarios are possible and reasonable. The next section presents the first of the developed models and afterwards some simulation results are shown.

1.1 Modelling

The first overall model is relatively simple, but already contains the main mechanical and electrical components of the main drive as well as the slides for automatic feed and infeed. The system is implemented in MATLAB / Simscape. Figure 2 shows the model part for the main drive with asynchronous motor, electrical control, voltage supply, gear belt drive, friction components and mechanical loads. The basic structure of the drive is easy to see which is helpful for further model adjustments, therefore pointing out one of the advantages of this object-oriented modelling approach.

The asynchronous motor as well as the servo motors for the remaining drives of the lathe and some of the basic mechanical components like gear belt drive, lead screw and linear bearings are modelled as Simscape components using the Simscape Language [5] with parameters extracted from available data sheets.

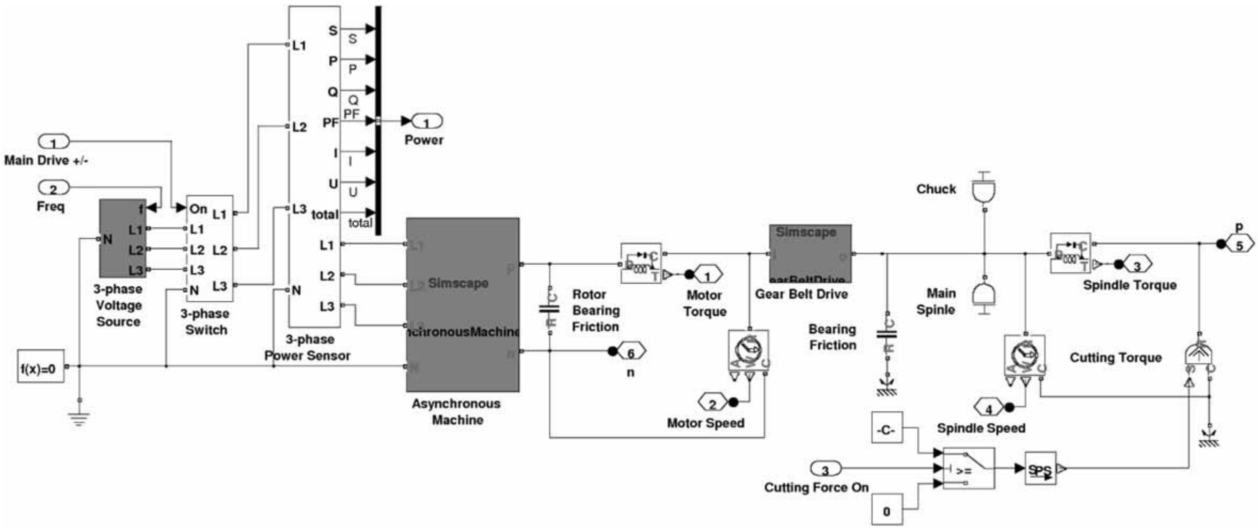

Figure 2. Main drive of the turning lathe model with power supply, electric control, asynchronous motor, gear belt drive, load and cutting force (over both columns).

A code fragment of this implementation for the asynchronous machine is shown in Listing 1. It implements common formulas for this electric drive in normalized space vector description.

```
component AsynchronousMachine
(...)
parameters (Access = public, Hidden = true)
   M=2/3*[1,-1/2,-1/2;0,sqrt(3)/2,sqrt(3)/2];
end
equations
(...)
   us'== M*[u1; u2; u3]; is'==M*[i1; i2; i3];
   i1+i2+i3==0;
   %Standardized equations for squirrel cage ASM
   Us == is*rs + psis.der/Omegaref el;
   ur == ir*rr + psir.der/Omegaref el...
        -[-psir(2),psir(1)]*omegam;
   psis == ls*is + ls*(1-sigma)*ir;
   psir == ls*(1-sigma)*(is+ir);
   ur == [0, 0];
   %Torque equation
   mr == is(2)*psir(1)-is(1)*psir(2);
end
```

Listings 1. Code fragment of asynchronous machine model in Simscape Language.

Existing Simscape blocks from the Simscape foundation library [6] complete the model with components for inertia, friction and sensor blocks for measuring state variables.

During the machining process, the cutting force generates an additional torque on the motor, which is calculated externally using common formulas and parameters [8].

Further parts of the overall model include similar drivetrains for both slides for automatic feed and infeed. In order to keep the first model simple, motor control, power electronics and thermal aspects are not yet taken into account. Instead, an ideal 3-phase voltage source directly provides appropriate voltage signals with variable frequency and amplitude controlled by external signals. This however limits possible simulation scenarios, for example only cases with constant motor speed can be considered.

1.2 Simulation Results

As output of this model, the results of a basic simulation run with the lathe are presented in Figure 3 It shows spindle speed, feed speed and cross-slide position during a single longitudinal machining process, also sketched in Figure 4. The process starts with the run-up of the main spindle, slide and cross-slide ar initialized with appropriate speed. When the cutting tool hits the workpiece (at about 3.8 s), cutting an feed forces set in causing disturbances in speed and displacement. Since there is no feedback motor control, the remaining deviation has to be accepted for this simple model. After the cutting tool has left the workpiece at time 13 s and a run-out length of 20 mm, main spindle and slide decelerate between 16.5 s and 17 s until they come to a stop.

For energy investigations, Figure 5 depicts the total power consumption for the described machining process. It stands out that the apparent power is exceptionally high during the acceleration phase of the main drive resulting from the simplified motor model and control.

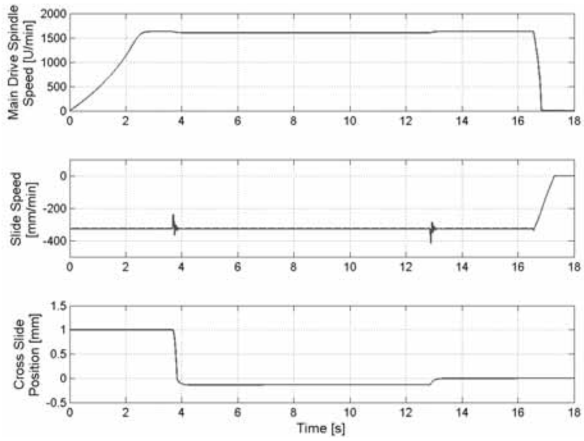

Figure 3. Simulation results of a basic simulation run: Spindle speed (top), slide speed (middle) and cross -slide position (bottom).

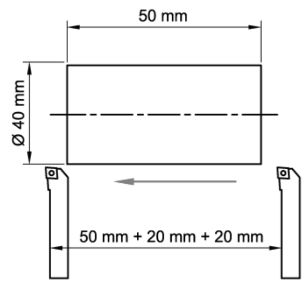

Figure 4. Schematic of the simulation run shown in Figure 3.

2 Thermal Coupling with the Environment

For the second part the thermal coupling of a machine tool with its environment shall be analyzed. In a first step two partial models are built. The first one is a model of a simple part of a machine tool, namely a linear guiding device, depicted in Figure 6, which is also provided by the Institute for Production Engineering and Laser Technology like the turning lathe from the first part of this study.

The second one is a model of the environment surrounding the machine, which is realized as a compartment model, a sketch of the discretization of the room can be seen in Figure 7.

It also depicts the machine that serves as a heat source for the room and is located in two different compartments, allowing it to distinguish between different heatsources within the machine, e.g. the electrical and the mechanical parts.

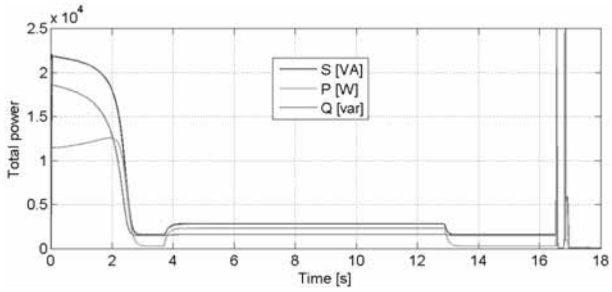

Figure 5. Total power consumption for all drives during the presented simulation run.

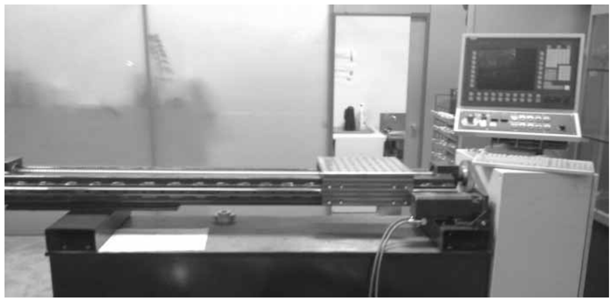

Figure 6. Test setup for the linear guiding device which is to be modelled.

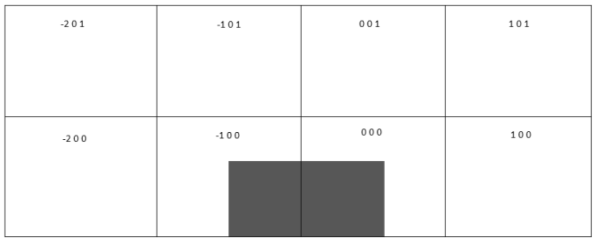

Figure 7. Schematic view of the discretisation and the two heat sources representing different parts of the machine.

2.1 Modelling

The linear guiding device as depicted in Figure 6 consists of a permanent magnet DC motor, a gear belt, a thread bar and the cart, where the mass is attached. In the model The motor is represented by a DC Permanent Magnet Motor block. For the gear belt, the gear ratio is modelled by a gear, the elasticity by a linear spring and the friction by a translational friction component.

The thread bar is modelled through its inertia and lead. Furthermore, the friction between the cart, the thread bar and the sliding mass are being taken into account. All components are from the Modelica Standard Library [9] and the model is implemented using MapleSim [7]. Figure 8 shows the model of the machine tool.

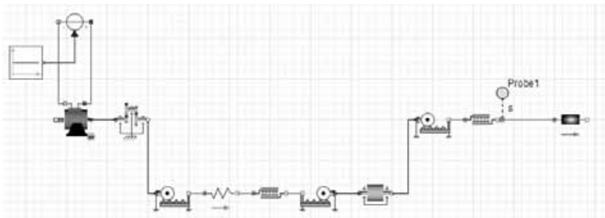

Figure 8. MapleSim model of the linear guiding device with blocks from the Modelica Standard Library.

For this first model, the source for the motor has a constant voltage, but it is planned that in further implementations measurement data will be incorporated. The parameters for the parts of the linear guiding device are taken from data sheets. For the model of the environment a room with the proportions 20m x 10m x 6m is assumed. In a first step, this room is discretised with eight compartments of equal volume, at first only two-dimensional for reasons of simplicity as can be seen in Figure 7. The modularity of the model structure suggests the usage of a single component that describes the whole compartment, which is depicted in Figure 9.

For the model several assumptions are made to keep it simple. First of all, the walls of the room are perfectly isolated, that means there is no heat exchange between the wall and the air. The only mechanism of heat exchange between the compartments is conductance, so there is no convection and the transfer is only permitted to adjacent compartments. Furthermore, the machine is the only source of heat in the room. For the parameters of the air, namely the density, specific heat capacity and thermal conductivity, we used typical values [10]. All parameters are assumed to be constant with a reference temperature of 20 °C.

The overall room model is depicted in Figure 10. It shows the modular structure of the model and the similarities to the schematics in Figure 7. The compartments are all equal in size, which is 5m x 5m x 6m and they are only horicontally and vertically connected, which respects the model assumption of the direction of the heat flow. On the bottom of the model there are two heat sources representing two different discretised part of the machine, which emit heat (motor, friction).

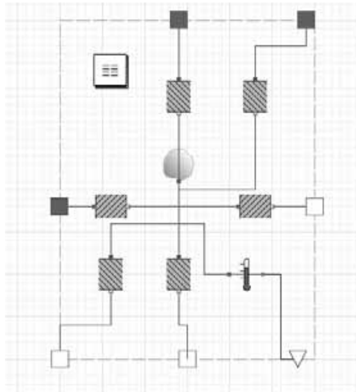

Figure 9. Single Compartment of room model in MapleSim.

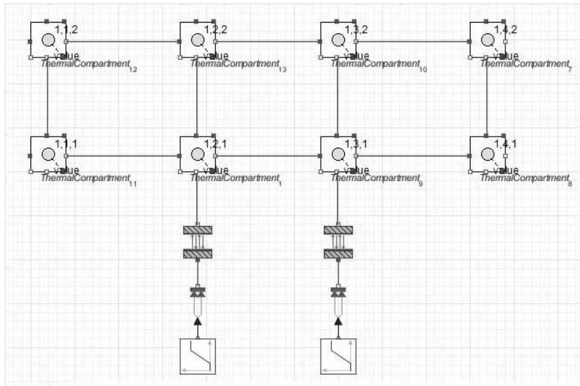

Figure 10. Thermal model of the discretised environment with eight compartments, two heat sources and conductive heat transfer.

2.2 Simulation Results

As mentioned before a constant voltage source was used for the first simulation runs of the linear guiding device. As a result the linear transalation of the sliding mass in shown in Figure 11.

The results are somewhat realistic in the way that you can see the run-up of the motor and the linear characteristics of the model in steady state.

The simulation of the room model starts with a running machine (i.e. it emits heat) and an initial temperature of 20 °C in all compartments. The machine runs for an hour, where the two different sources constantly emit a certain amount of heat. After that, the machine is turned off and is cooling down during the next four hours, cf. Figure 12. Figure 13 shows the development of the temperature in each compartment.

One can observe that the biggest increase of temperature is in the compartment with the stronger heat source. The compartments adjacent to it have an observable increase of temperature after a short time and the compartments further away are heating up much slower.

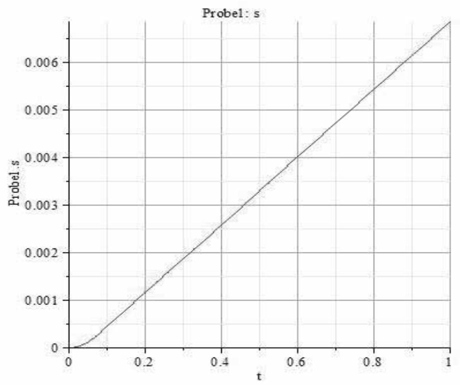

Figure 11. Acceleration and linear translation of the sliding mass over time.

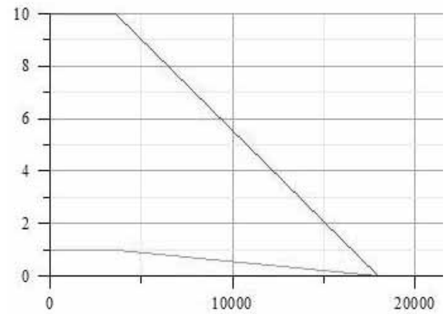

Figure 12. Heat emission of the two different sources over time.

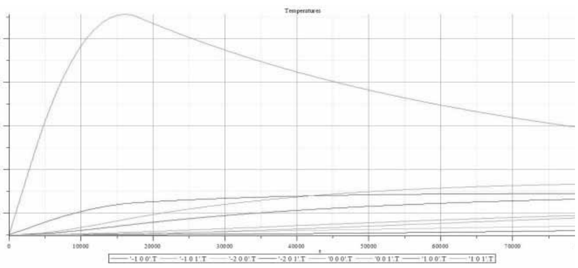

Figure 13. Temperatures in the different compartments over time.

There is also a little difference between the trajectory of the compartment with the lesser heat source in it and the other compartments without a heatsource, but the amount of emitted heat is too low to make an significant impact. Furthermore it can be seen, that the temperatures in the compartments are approaching a steady state, where the temperature is equal for all compartments.

3 Summary and Conclusion

The object-oriented modelling approach is confirmed to be a suitable tool for multi-domain modelling and thermal considerations of machine tools resulting in modular models, which can easily be modified and refined.

However, simulations show that the models are comparatively complex with a larger amount of equations compared to classical equation-oriented modelling which leads to less efficient numerical simulations resulting in higher computation times. Especially multi-domain applications usually lead to stiff equation systems that require additional effort during simulation.

4 Outlook

Future work regarding the studies shown in this paper will focus on refinement of the models, e.g. for detailed investigation of thermal aspects of the machine tool, and on the coupling of the models that have been presented. For model validation it is planned to obtain measurement data from the turning lathe as well as the linear guiding device and compare these measurements with corresponding results from the simulation.

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