STUDIES ON THE THERMODYNAMICAL COUPLING OF A MACHINE TOOL AND ITS ENVIRONMENT USING THE OBJECT-ORIENTED MODELLING APPROACH OF MODELICA

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ABSTRACT

As the necessity of lowering the energy consumption of manufacturing plants rises, the possibility to optimize a planned production hall becomes more and more important. Therefore the research project INFO, a project of the Vienna University of Technology in cooperation with industry partners and supported by the FFG, the Austrian Research Promotion Agency, creates an overall simulation of a cutting factory. This work deals with one aspect of such a simulation by studying the possibilities of coupling different partial models in one simulator. First the two partial models are built and their simulation results are compared to measurement data. The models are kept very simple to avoid numerical problems that could emerge from having an equation system that is too big. Then the two models are coupled and the problems that arise are analysed.

Keywords: thermodynamics, machine tool, Modelica, Dymola, MapleSim

1. INTRODUCTION

As the necessity of lowering the energy consumption of manufacturing plants rises due to increased energy costs and environmental awareness, the possibility to optimize a planned production hall becomes more and more important. Therefore the research project INFO, a project of the Vienna University of Technology in cooperation with industry partners and supported by the FFG, the Austrian Research Promotion Agency, creates an overall simulation of a cutting factory. This includes microscopic and macroscopic processes, like machines, the building hull or influences of the weather, where all manifestations of energy in and the energy flow between the single components are studied (Leobner, Ponweiser, Neugschwandtner and Kastner 2011). Because of the multitude of the used models, one aspect of the project is to study the possibilities and difficulties of coupling different model parts.

In this paper the coupling of different model parts in one simulator will be studied. Therefore a model of a machine tool and a room model, which are then coupled, are chosen. The models are kept simple to identify the problems that occur because of the coupling of the model parts rather than numerical problems because of the size of the resulting equation system. The model of the machine tool is a linear guiding device and for the room model a compartment model is chosen. For both models exist test rigs, so they can be validated against measurement data.

Additionally a comparison of two different simulators, Dymola and MapleSim, is made. Both simulators rely on the same modelling approach, so their numerical behaviour and efficiency can be studied.

2. SIMULATORS

The Modelica Standard, which is maintained by the Modelica Corporation, uses an object-oriented approach to model physical systems. The system is simulated by building an acausal block-diagram, where every block represents a real component, for instance a linear translational spring. By using the defining equations for each component, which are stored in the representing blocks, and additional equations, that result from combining the blocks with acausal connections, an equation system is built, which can be solved by a simulator. It is important to note, that neither in the components nor in the connections a causality between the variables is assumed.

This approach works in various physical domains such as mechanics, electrical engineering or thermodynamics, which makes it possible to build multi-domain models. The Modelica Standard only provides a language to describe models in such a manner, to simulate the models a simulator, which understands this language and provides the necessary algorithms to derive and solve the resulting equation system, has to be used. The current version of the Modelica Standard is version 3.2 (Modelica Corporation 2010).

As mentioned before two different simulators are used in this paper: Dymola and MapleSim. These simulators shall now be described briefly laying a focus on the functionalities used in this paper.

2.1. Dymola

The past of Dymola is closely related to Modelica as the Modelica Standard is developed from Dymola. Because of this Dymola can be seen as the simulator who understands the Modelica language best. Models can be built either graphically or textually. The version used in this paper is Dymola 2012, which supports the Modelica Standard 3.2. One of the main advantages is that all dissipative components have an optional heatport, which allows the use of the lost energy in an additional thermodynamical system.

2.2. MapleSim

MapleSim is developed by MapleSoft. Models can only be built graphically, but new components can be defined using either the Modelica language or a built in Maple function, where only the equations and ports have to be defined and a Modelica component is created automatically. MapleSim supports Modelica Standard 3.1, where the optional heatport is only used in the electrical resistor component; this means that for the other dissipative components the lost energy has to be measured to be used in a thermodynamical model.

3. MACHINE MODEL

The linear guiding device is a simple part of a machine tool; it consists of a permanent magnet DC motor that drives a thread bar via a gear belt. The thread bar moves a cart, where the sliding mass is attached. The test setup for the validation of the model is provided by the Institute for Production Engineering and Laser Technology from the Vienna University of Technology (Salvatori 2012) and is shown in Figure 1.



Figure 1: Test setup of linear guiding device

For the model components of the Modelica Standard Library were used, the general structure of the model can be seen in Figure 2. It shows that the structure of the model is very similar to the structure of the real system, which is an important advantage of this modelling approach.



Due to the graphical representation of the model and the modular structure, the underlying equations are not easy to see, so the individual components of the model are described the following sections.

3.1. Permanent Magnet DC Motor

The electric motor is implemented as a permanent magnet DC motor model (Kral and Haumer 2011). The motor model was updated in version 3.2 of Modelica, so the models in Dymola and MapleSim differ in their complexity. Figure 3 depicts the model in Dymola.



Figure 3: Model of a Permanent Magnet DC Motor in Dymola

It can be seen that many losses are taken into account in the model as many of the components have heatports, which are illustrated as red squares. Besides the heat losses in the armature winding resistance, which is modelled as a resistor component, the other power losses that are considered are

- Brush losses in the armature circuit
- Friction losses
- Core losses
- Stray load losses

The sole purpose of the four components is to model the respective losses, where the power loss depending on the angular velocity or the current is calculated. By setting these dependencies to zero the components have no impact on the simulation results, which will be important to compare the Dymola and the MapleSim model. As mentioned before the MapleSim model of the permanent magnet DC motor is not that complex, here the armature circuit is modelled as a inductor and a resistor connected in series. Because of that the only power losses that can be taken into account are the losses in the resistor component so for comparability reasons the losses in the other components of the Dymola model have to be zero.

The parameters for the component were taken from the datasheets of the motor used in the test setup.

3.2. Gear Belt

The spring constant of a gear belt is always given in a translational manner in the data sheets. Therefore it is modelled as a linear translational spring-damper element, where the damping constant of the component is chosen in such a way that a swinging up of the spring is prevented. The transition between the rotational and translational mechanical domain is made through ideal gears, so no power is lost in this transition.

3.3. Thread Bar

The defining parameters for a thread bar are its inertia and its lead. So the thread bar in this model consists of a inertia component and an ideal gear, where the transition ratio is directly proportional to the lead of the thread bar.

3.4. Cart and Mass

As the cart and the mass that shall be moved are rigidly connected to each other, they can be modelled as one mass. The component chosen for the model is a mass with stop and friction, where also a hard stop can be implemented, but is not considered for this model.



Figure 4: Characteristics of the velocity dependent friction force in Modelica

The friction model that is used in Modelica is called Stribeck friction model. It not only takes into account the static and the velocity dependent friction but also considers the so called Stick-Slip-Effect. This is modelled by an additional term that models the friction decreasing exponentially with rising velocity of the mass. The dependencies between friction force and velocity are depicted in Figure 4, which are taken from the documentation of the Modelica Standard Library.

The parameters of the friction were chosen in such a way, that the measurement data was approximated properly by the simulation results. This can be justified by the fact that the other mechanical components in the model are implemented at least nearly ideal, so the friction component can be seen as a cumulative component, where all the mechanical frictions in the system are considered.

3.5. Voltage Source

The input for the voltage source, that supplies the voltage for the electric motor, is stored in a time table. The entries of the table are derived from measurement data. The data was taken over the course of one displacement process. The measuring equipment was placed in front of the power electronics, so the first step of adjusting the data was to subtract the mean value of the data points in the idle state, because the power electronics is not considered in the model. Additionally, because the measured signal was very noisy, the data was filtered by a very simple algorithm. Every data point v_i is replaced with the mean value of $v_{i-2}, v_{i-1}, v_i, v_{i+1}, v_{i+2}$. This procedure is repeated ten times. The result of the filtering is depicted in Figure 5.



Figure 5: Input-Signal of Voltage Source before and after filtering

3.6. Simulation Results

To compare the simulation results with the measurement data the power consumption of the electric motor was used. Therefore the voltage and current in the armature circuit of the motor was measured in the model and then multiplied.

The first simulation runs were made using the unfiltered noisy signal on the left of Figure 5. The simulation results showed that the two simulators had very big problems to simulate the system. The results of the two simulators were very different depending very much on the solver algorithm, the step sizes. Additionally the simulation results had no real connection to the measurement data, because the noise in the input signal got stronger during the simulation. Given the model does not account for the power electronics, the power consumption of the controller has to be added to simulation results, so they can be compared to the measurement data. Figure 6 and 7 show the results of the simulation runs in Dymola and MapleSim compared to the measurement data. Additionally the mean values of the power consumptions over time are shown.



Figure 6: Simulation results in Dymola



Figure 7: Simulation results in MapleSim

A qualitative analysis shows that the results of both simulators match the measurement data very well. Comparing the two simulators it can be seen that the results are slightly different. Also the mean values over the displacement period are different. Dymola matches the measurement data better in this regard, whereas the machine in MapleSim consumes lesser power over the course of one period.

4. ROOM MODEL

The surrounding of the machine is modelled through a compartment model. This means that the room model is discretized into compartments. The individual compartments can be seen as boxes of a certain size containing air. In reality such a model would have to take into account many things, so several assumptions are made for the model to simplify it:

- The temperature is constant within the compartment
- Heat flow is only permitted over the contact surface of adjacent compartments
- The only way of heat transport is conduction, no convection or radiation is taken into account.
- The walls of the room are perfectly isolated. No heat flow over the boundaries is permitted, so there is no energy lost in the system.
- The thermal parameters of the air are assumed to be independent from the temperature and therefore constant over time.

4.1. Compartments

Each compartment is implemented as a submodel. Figure 8 shows the basic structure of the compartment.



Figure 8: Basic structure of a single compartment in Dymola

In Figure 9 the parameters for the compartment block are shown. The size of the compartment is given by the expansion along the x-, y- and z-axis, which have to be adjusted to the used compartments. Other parameters that are used by the components within the compartment are derived directly like the volume or the area of the faces of the compartment. Also the thermal parameters of the medium, that the compartment is filled with, can be adjusted. The parameters are the specific thermal capacity, the density and the conductivity of the medium. As default the parameters are set to values that correspond to the thermal properties of air at 20° C.

The components used in the compartment submodel use these parameters to calculate the heat flow between the compartments. The heat capacitor which is located in the middle of the block depends on the thermal mass of the compartment, which can be derived from the volume and the specific thermal capacity. In the heat capacitor component the temperature of the compartment is calculated.



Figure 9: Parameters for the Compartment-block

Furthermore six conductor components for all possible directions of the heat transfer are implemented. To derive the heat flow through these components, the simple geometry of the compartment is used. The heat flow is then only dependent on the area of the contact surface between two compartments, the distance between the centres of the two, the thermal conductance of the medium and their temperature difference.

At last a temperature sensor to measure the temperature in the compartment is added.

4.2. Validation

For the validation of the model a test rig was built to see if the assumptions made for this model are too restrictive. Therefore a Styrofoam box was used, where eight temperature sensors were attached inside. As a heat source a soldering rod was used. The parameters of the eight compartments used in this model are depicted in Figure 9, the test rig and the model can be seen in Figure 10.



Figure 10: Test rig for the room model and model in MapleSim

The measurement data of the test rig can be seen in Figure 11, the simulation results of Dymola and MapleSim in Figure 12.



Figure 11: Measurement data of test rig for room model



Figure 12: Simulation results from Dymola and MapleSim

It can be seen that the qualitative behaviour of the temperature in the compartment, where the heat source is attached, matches the measurement data, but the magnitude of the temperature rise in the simulation is disproportional. An explanation for this effect can be that the test rig is not isolated well enough, so the assumption of the perfectly isolated walls cannot be met. Further the other compartments heat up much more uniformly in the experiment than in the simulation. This has two main reasons. First in the test rig the heat can flow in any direction, whereas in the simulation it is only permitted in six. Second the convection, which is neglected in the simulation, allows a much smoother heat distribution in the experiment.

The comparison of the simulation results shows that the two simulators work equally good for this model.

5. COUPLING

In a final step the two models are coupled into one model. The energy lost in the dissipative components of the machine model is used as heat source for the room model. In the coupled model the machine stretches across two compartments. The heat loss of the electric motor is a heat source of one compartment and the heat lost through friction in the mechanical parts heats up another compartment. Figure 13 shows the coupled model.



Figure 13: Coupled model in MapleSim

To model a machine hall the compartments in this model are much larger. The machine hall is assumed to have an expansion of $20m \times 10m \times 6m$. Additionally changes in the machine model had to be made. In Dymola it was possible to activate the optional heatports to get the heat loss in the dissipative elements, whereas in MapleSim it was necessary to build a new permanent magnet DC motor component to retrieve the energy lost in the resistor of the armature circuit and to measure force and velocity at the friction component to calculate the heat from this component. Figure 14 depicts the simulation results in Dymola for a simulation time of six hours.



Figure 14: Simulation results of the coupled model in Dymola

More interesting than the simulation results itself are the computation times it took to simulate the model. The two simulators both needed about half an hour to compute this relative simple model. Seeing as the used models are too simplified to represent a real machine or machine hall leads to the conclusion that for more complicated models a coupling in one simulator is nearly impossible even with bigger computational power.

The main problem in coupling the two models arises because of the different time constants of the model parts. As the time constants for the electrical and the mechanical part of the machine model are similar, the thermal time constant is proportional to the thermal mass of the studied system. This has the effect that very small steps have to be made by the solver algorithm compared to the relatively large simulation time and in each of these time steps the whole thermal model has to be calculated, which would not be necessary because of the slowly changing behaviour of the system. This can also lead to numerical problems through loss of significance.

6. CONCLUSION

For these particular models it is possible to couple them in one simulator, this is due to the simplicity of the models. As mentioned before having bigger, more complex models would take much more computational effort to simulate. To simulate a whole production hall over the course of a year is therefore not advisable with this approach.

For the machine model it is to say, that it provides satisfactory results if the input signal is smooth enough.

The room model is not sophisticated enough to represent a real room, for that the model assumptions are too restrictive. But the modular construction of the room model allows an easy refinement of the discretization of the model.

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