Object-oriented Modelling of Machine Tools for Energy Efficiency Analysis in Production

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Abstract: There are a number of research projects with the aim of increasing energy efficiency in production. One of them, the research project INFO, attempts to make qualified predictions about the effectiveness of different energy saving approaches by using a comprehensive simulation model of production halls including all micro- and macro-structures. In order to gain knowledge about the optimization potential in the micro-structures of production plants, simulation models of typical machine tools are developed for energy analysis. Using object-oriented modelling for physical systems allows combining component models of mechanical, electrical and thermal parts in one multi-domain model. This bottom-up approach is combined with stepwise top-down modelling in several stages in order to identify numerical boundaries and the level of modelling detail necessary for investigating certain physical aspects.

Keywords: Machine tool, Object-oriented modelling , Energy efficiency, Turning lathe, Physical modelling, Simscape

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1. INTRODUCTION

The research project INFO (sponsored by the Austrian Research Promotion Agency (FFG)) 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 holistic approach (see also Dorn and Bleicher (2010)). Qualified and customized predictions and recommendations about the efficiency of different energy saving measures can be made using comprehensive simulation models of the real production plant including all relevant micro- and macro-structures and therefore identify potential savings in manufacturing plants (cf. Stark et al. (2010)).

One important part of this project investigates the micro-structures of production plants (individual processes and machines) by making extensive energy analysis to point out optimization potential based on simulation models. This also allows gaining knowledge for merging the individual levels in the modelling approach to an ultimately complete simulation. Some of these aspects are studied in more detail by creating a multi-domain model of a turning lathe as an example of a machine tool.

For modelling we consider a new high-level object-oriented modelling approach, which provides the necessary flexibility regarding modularity and reusability. The structured nature of this modelling method allows for simple stepwise development and easy expandability of a multi-domain model including electrical, mechanical and thermal aspects of the machine tool. Simulation results are validated against real measurement data obtained from the actual turning lathe, of which the model is created and which is provided by the Institute for Production Engineering and Laser Technology from the Vienna University of Technology.

Although simulators for object-oriented component-based modelling of physical systems have evolved considerably in the last years (e.g. Dymola, MATLAB/Simscape™, MapleSim), there are still numerical issues when it comes to simulating complex multi-domain systems. Bottom-up modelling of this component-based approach is therefore combined with stepwise top-down modelling in several stages with gradually increasing level of detail for identifying numerical boundaries of the simulation arising from higher level of modelling detail as well as the degree of modelling effort necessary for investigating certain aspects.

Although we consider applications for energy analysis and optimization, we also try to investigate object-oriented modelling as concept for modelling machine tools. Therefore we also consider aspects, which might not be relevant in pure energy applications, but are necessary for accurate physical modelling. We also want to see which model complexity can be handled with sufficient performance and which physical components can therefore be taken into account.

2. SIMPLE MODEL

For implementing the developed simulation models, we chose Simscape as an extension of MATLAB/Simulink for object-oriented multi-domain modelling and simulation of physical systems (see also MathWorks (2011a) and MathWorks (2011b)).

Observing the turning lathe, which is to be modelled, shows that it consists of three main modules: The main drive for the spindle, a slide for automatic feed and a cross-slide for infeed. Although this machine tool is rather simple compared to others, it provides sufficient possibilities for our investigations.

2.1 Modelling

The first overall model is relatively simple and contains the main mechanical and electrical components of the main drive as well as of the slides for automatic feed and infeed. As part of this first model, Fig. 1 shows the Simscape model of the main drive with asynchronous engine, voltage supply, gear belt drive, friction components and mechanical loads such as inertias from spindle, chuck and workpiece. The basic structure of the drive is easy to see which is helpful for further model adjustments and refinements, therefore pointing out one of the big advantages of this object-oriented modelling approach.

The asynchronous motor as well as the servo motors for the remaining drives of the lathe and certain basic mechanical components like gear belt drive, lead screw and linear bearings are modelled as Simscape components using Simscape Language (see MathWorks (2011a)) with parameters extracted from available data sheets. A code fragment of this implementation for the asynchronous machine is depicted in Fig 2. It shows common formulas in normalized space vector description.

Existing Simscape blocks from the Simscape Foundation library (see MathWorks (2011b)) 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. This load is modelled as a torque source, where the value of the torque is calculated externally using common formulas and parameters (like shown in Degner et al. (2009)).

```
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
```

Fig. 2. Code fragment of asynchronous machine model in Simscape Language

In order to keep the first model simple, we did not take the motor control or power electronics like converter into account. Instead, a 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. Also, thermal investigations are not yet provided in this model.

2.2 Simulation Results

As output of this model, some results of a basic simulation run can be seen in Fig. 4. It shows Spindle speed, feed speed and infeed position during a single longitudinal turning process, which is also sketched in Fig. 3. The simulation starts with a run-up of the main spindle, slide and cross-

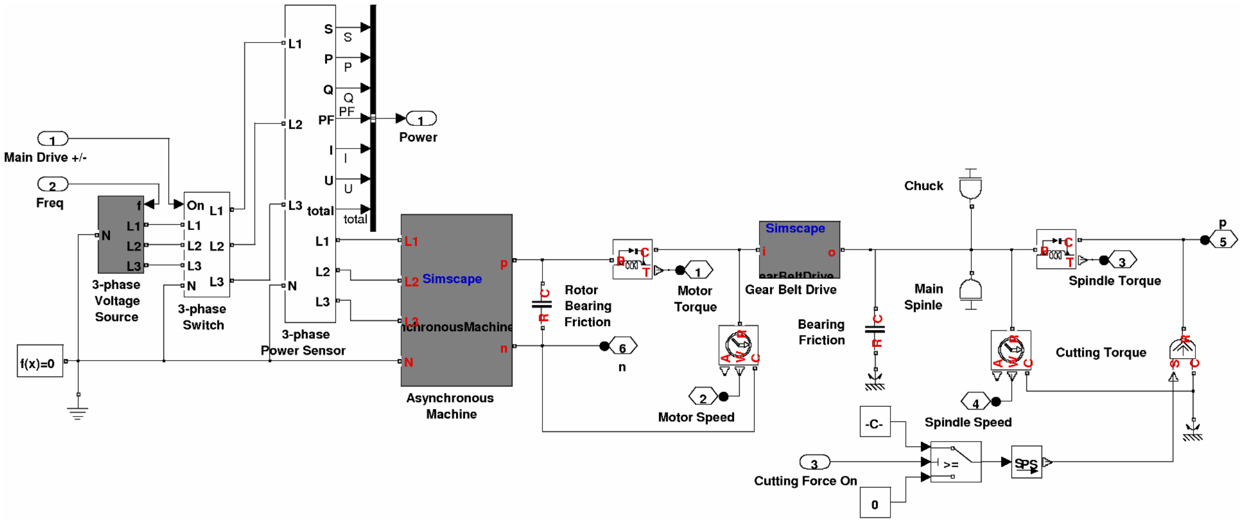

Fig. 1. Main drive of the turning lathe model with asynchronous engine, voltage supply, gear belt drive and mechanical loads

slide are initialized with appropriate speed. When the cutting tool hits the workpiece (at about 3.8 s), cutting and feed forces set in, causing disturbances in speed and displacement values. This is most clearly recognized in the infeed position of the cross-slide (bottom of Fig. 4). Since there is no feedback motor control implemented, 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 beginning at 16.5 s until they stop at 17 s.

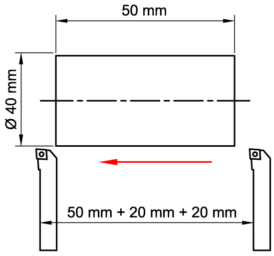

Fig. 3. Sketch with workpiece and cutting tool of the simulated single longitudinal turning process

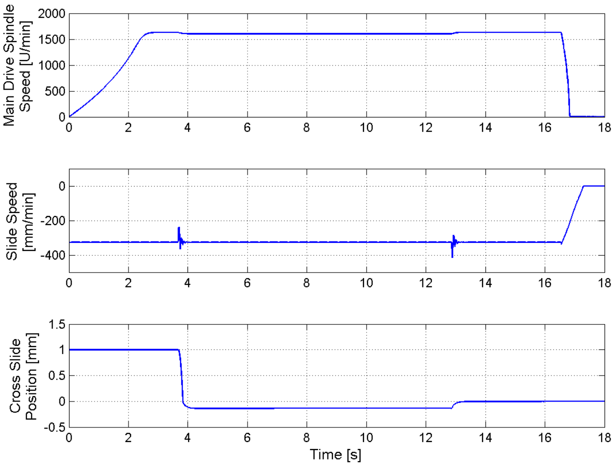

Fig. 4. Simulation results of a basic simulation run: Spindle speed (top), feed speed (middle) and infeed position (bottom)

For energy investigations, Fig. 5 depicts the total power consumption during the described simulation run. It stands out that the power consumption is exceptionally high during the acceleration phase of the main drive at the beginning, which results from linear equation models for the drive motors as well as the simplified motor control without limitation of acceleration.

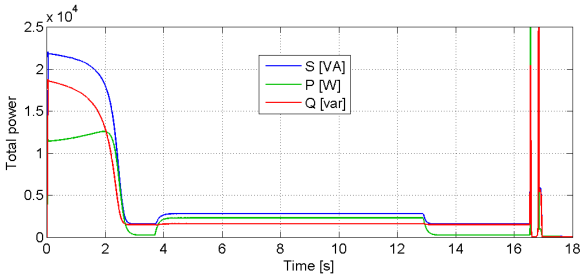

Fig. 5. Total power consumption during simulation

3. REFINED MODEL WITH MOTOR CONTROL

The first modelling stage showed that the object-oriented modelling approach is indeed suitable for basic modelling tasks of machine tools. In this next stage we further develop the model and therefore obtain further possible simulation scenarios for observation.

3.1 Modelling

We extend the first simple simulation model described in section 2 by more accurate motor control parts in order to get more realistic simulation results. How important appropriate motor control is for the overall dynamics is shown in the simulation output in the previous section (see Fig. 4), where the simplified motor control without feedback loop led to permanent steady-state error in the infeed position. Fig. 6 shows the implemented feedback control subsystem in the typical structure with position controller, speed controller and current controllers, which adjust both values in the rotor coordinate system separately. Since the current values are measured only in the stator coordinate system and the voltage values also have to be adjusted in the stator coordinate system, coordinate transformation has to be performed before and after. For creating the feedback control, we made use of available data sheets. However, some adjustments had to be made in order for the system to work properly. A position control block generates set values for the controllers with speed and acceleration limits according to target positions which are defined in advance.

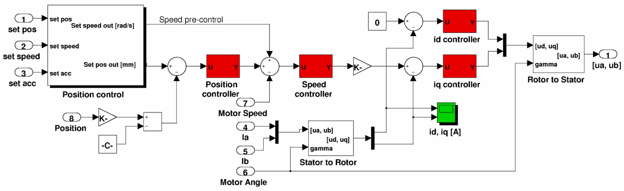

Fig. 6. Slide control with position, speed and current controller and space vector output

The output of the controller subsystem is a voltage space vector in the stator coordinate system, which is then split into phase voltages for the 3-phase converter, which supplies the drive motor. Since we did not succeed with a model implementation of a switching inverter (like they are used in real applications) with sufficient performance especially regarding simulation time, we decided to implement a simplified idealized version with independent voltage sources, which directly supply appropriate phase voltages. The respective part of the power supply is exemplified for the servomotors shown in Fig. 7.

Additionally, the Simscape blocks for the electric machines are now equipped with a thermal output port (this can also be seen in Fig. 7) for investigation of energy losses.

3.2 Simulation Results

The implemented motor control now allows for more complex simulation scenarios. As an example, we investigate the turning process sketched in Fig. 8. The respective simulation results are shown in Fig. 9. All position values

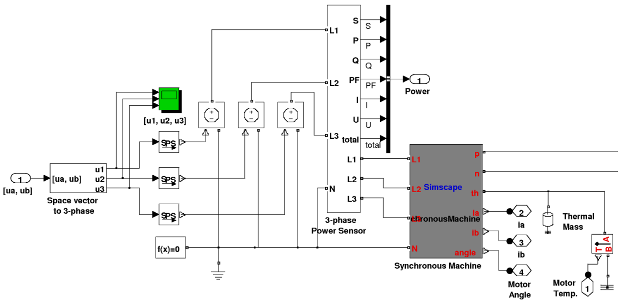

Fig. 7. Part of the refined slide model with idealized converter as independent voltage sources

are measured in the coordinate system illustrated in Fig. 8 (green arrows). The simulation starts at an outside position. First, slide and cross-slide are activated with maximum velocity in order to get to the start position for the turning process. After that, the turning process is started with smaller feed velocity. The impact point between toll and workpiece does not leave a noticeable disturbances. The process is finished with negative infeed to the end position. Note that all manoeuvres have specified maximum values for velocity and acceleration.

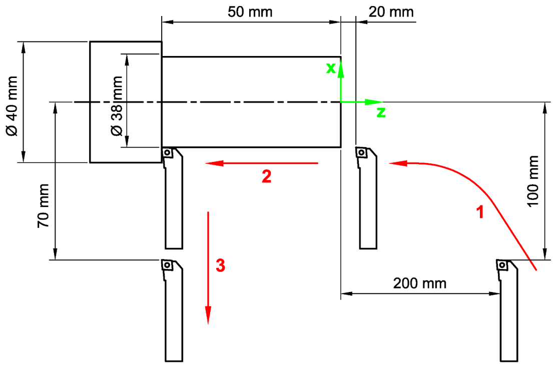

Fig. 8. Sketch with workpiece and cutting tool of the second simulation scenario

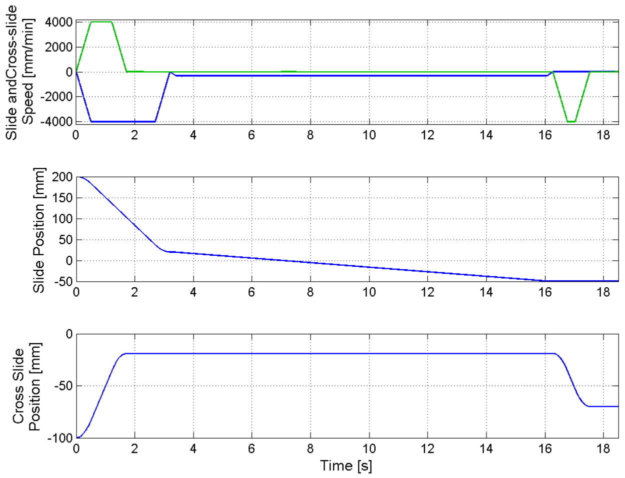

Fig. 9. Simulation results of second simulation run: Slide and cross-slide speed (top), slide position (middle) and cross-slide position (bottom)

4. CONCLUSION AND OUTLOOK

It can be said that object-oriented modelling is a suitable tool and offers practical ways for structured multi-domain modelling of machine tools leading to modular systems which can easily be modified and adapted. However, this approach leads to comparatively complex models with a larger amount of equations, which can profoundly affect the performance during simulation.

Further model refinements are planned as part of the next stages in the top-down modelling process, especially for more detailed investigation of thermal aspects including heating of the workpiece. In addition, remaining (constant) electrical loads of the turning lathe such as the control computer or lighting have to be considered because they have influence on the overall power consumption and they are necessary for obtaining matching results with measurement data from the actual turning lathe. Also, it is planned to expand the calculation model for cutting and feed forces in order to increase accuracy and factor in tool wear influences. For model validation we will compare the simulation results of various scenarios against measurement data obtained from the turning lathe.

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