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Multi-Domain Simulation:
Mechanics and Hydraulics of an Excavator

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Abstract

It is demonstrated how to model and simulate an excavator with Modelica and Dymola by using Modelica libraries for multi-body and for hydraulic systems. The hydraulic system is controlled by a "load sensing" controller. Usually, models containing 3-dimensional mechanical and hydraulic components are difficult to simulate. At hand of the excavator it is shown that Modelica is well suited for such kinds of system simulations.

1. Introduction

The design of a new product requires a number of decisions in the initial phase that severely affect the success of the finished machine. Today, digital simulation is therefore used in early stages to look at different concepts. The view of this paper is that a new excavator is to be designed and several candidates of hydraulic control systems have to be evaluated.

Systems that consist of 3-dimensional mechanical and of hydraulic components – like excavators – are difficult to simulate. Usually, two different simulation environments have to be coupled. This is often inconvenient, leads to unnecessary numerical problems and has fragile interfaces. In this article it is demonstrated at hand of the model of an excavator that Modelica is well suited for these types of systems.

The 3-dimensional components of the excavator are modeled with the new, free Modelica MultiBody library (Otter et. al. 2003). This allows especially to use an analytic solution of the kinematic loop at the bucket and to take the masses of the hydraulic cylinders, i.e., the "force elements", directly into account. The hydraulic part is modeled in a detailed way, utilizing pump, valves and cylinders from HyLib, a hydraulics library for Modelica. For the control part a generic "load sensing" control system is used, modeled by a set of simple equations. This approach gives the required results and keeps the time needed for analyzing the problem on a reasonable level.

2. Modeling Choices

There are several approaches when simulating a system. Depending on the task it may be necessary to build a very precise model, containing every detail of the system and needing a lot of information, e.g., model parameters. This kind of models is expensive to build up but on the other hand very useful if parameters of a well defined system have to be modified. A typical example is the optimization of parameters of a counterbalance valve in an excavator (Kraft 1996).

The other kind of model is needed for a first study of a system. In this case some properties of the pump, cylinders and loads are specified. Required is information about the performance of that system, e.g., the speed of the pistons or the necessary input power at the pump shaft, to make a decision whether this design can be used in principle for the task at hand. This model has therefore to be "cheap", i.e., it must be possible to build it in a short time without detailed knowledge of particular components.

The authors intended to build up a model of the second type, run it and have first results with a minimum amount of time spent. To achieve this goal the modeling language Modelica (Modelica 2002), the Modelica simulation environment Dymola (Dymola 2003), the new Modelica library for 3-dimensional mechanical systems "MultiBody" (Otter et al. 2003) and the Modelica library of hydraulic components HyLib (Beater 2000) was used. The model consists of the 3-dimensional mechanical construction of the excavator, a detailed description of the power hydraulics and a generic "load sensing" controller. This model will be available as a demo in the next version of HyLib.

3. Construction of Excavators

In Figure 1 a schematic drawing of a typical excavator under consideration is shown. It consists of a chain track and the hydraulic propel drive which is used to manoeuvre the machine but usually not during a work cycle. On top of that is a carriage
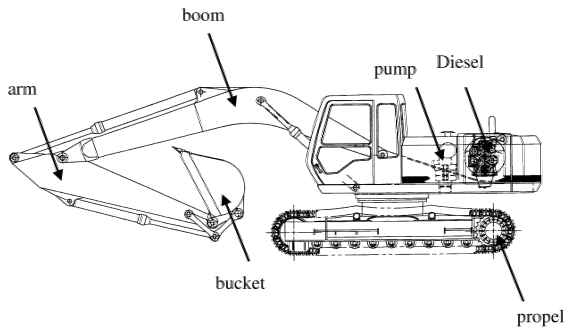
Figure 1 Schematic drawing of excavator

where the operator is sitting. It can rotate around a vertical axis with respect to the chain track. It also holds the Diesel engine, the hydraulic pumps and control system. Furthermore, there is a boom, an arm and at the end a bucket which is attached via a planar kinematic loop to the arm. Boom, arm and bucket can be rotated by the appropriate cylinders.

Figure 2 shows that the required pressures in the cylinders depend on the position. For the "stretched" situation the pressure in the boom cylinder is 60 % higher than in the retracted position. Not only the position but also the movements have to be taken into account. Figure 3 shows a situation where the arm hangs down. If the carriage does not rotate there is a pulling force required in the cylinder. When rotating – excavators can typically rotate with up to 12 revolutions per minute – the force in the arm cylinder changes its sign and now a pushing force is needed. This change is very significant because now the "active" chamber of the cylinder switches and that must be taken into account by the control system. Both figures demonstrate that a simulation model must take into account the couplings between the four degrees of freedom this excavator has. A simpler model that uses a constant load for each cylinder and the swivel drive leads to erroneous results (Jansson et al. 1998).
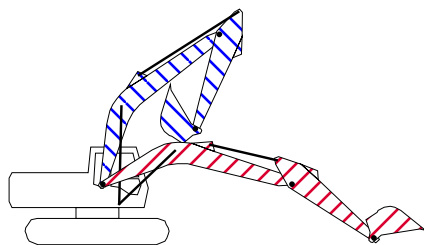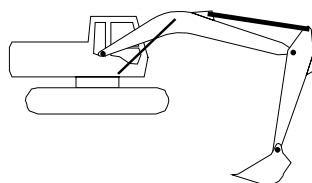

Figure 2 Different working situations

Figure 3 Effect of centrifugal forces

4. Load Sensing System

Excavators have typically one Diesel engine, two hydraulic motors and three cylinders. There exist different hydraulic circuits to provide the consumers with the required hydraulic energy. A typical design is a Load Sensing circuit that is energy efficient and user friendly. The idea is to have a flow rate control system for the pump such that it delivers exactly the needed flow rate. As a sensor the pressure drop across an orifice is used. The reference value is the resistance of the orifice. A schematic drawing is shown in figure 4, a good introduction to that topic is given in (anon. 1992).

The pump control valve maintains a pressure at the pump port that is typically 15 bar higher than the pressure in the LS line (= Load Sensing line). If the directional valve is closed the pump has therefore a stand-by pressure of 15 bar. If it is open the pump delivers a flow rate that leads to a pressure drop of 15 bar across that directional valve. Note: The directional valve is *not* used to throttle the pump flow but as a flow meter (pressure drop that is fed back) and as a reference (resistance). The circuit is energy efficient because the pump delivers only the needed flow rate, the throttling losses are small compared to other circuits.

If more than one cylinder is used the circuit becomes more complicated, see figure 5. E.g. if the boom requires a pressure of 100 bar and the bucket a pressure of 300 bar the pump pressure must be above 300 bar which would cause an unwanted
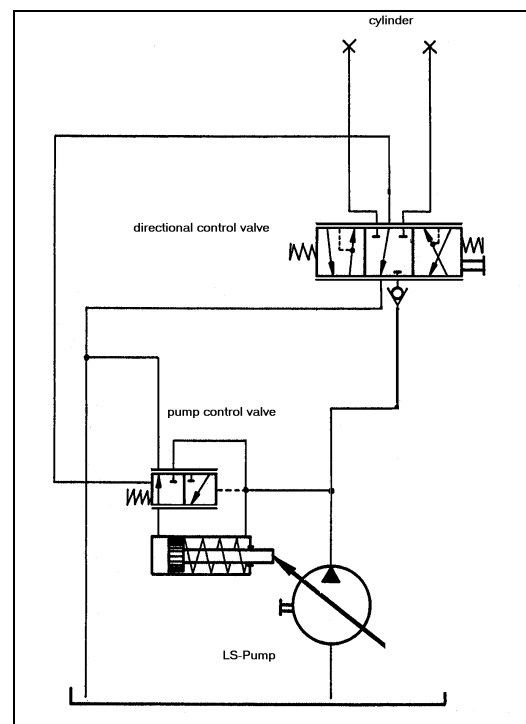

Figure 4 Schematics of a simple LS system (Zähe)

movement of the boom cylinder. Therefore compensators are used that throttle the oil flow and thus achieve a pressure drop of 15 bar across the particular directional valve. These compensators can be installed upstream or downstream of the directional valves. An additional valve reduces the nominal pressure differential if the maximum pump flow rate or the maximum pressure is reached (see e.g. Nikolaus 1994).
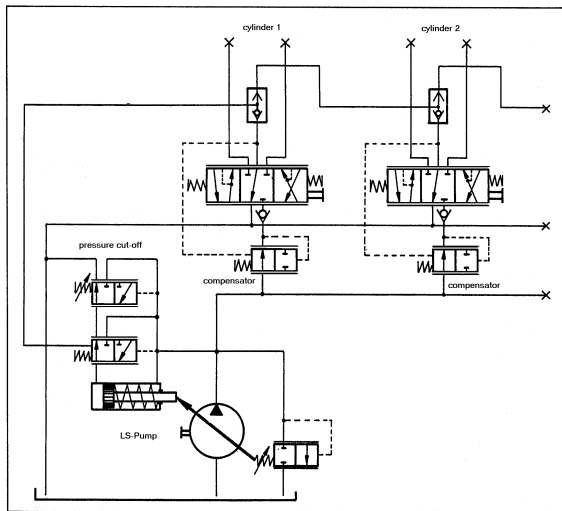

Figure 5 Schematic drawing of a LS system

5. Model of Mechanical Part

In Figure 6, a Modelica schematic of the mechanical part is shown. The chain track is not modeled, i.e., it is assumed that the chain track does not move. Components "rev1", ..., "rev4" are the 4 revolute joints to move the parts relative to each other. The icons with the long black line are "virtual" rods that are used to mark specific points on a part, especially the mounting points of the hydraulic cylinders. The light blue spheres (b2, b3, b4, b5) are bodies that have mass and an inertia tensor and are used to model the corresponding properties of the excavator parts.

The three components "cyl1f", "cyl2f", and "cyl3f" are line force components that describe a force interaction along a line between two attachment points. The small green squares at these components represent 1-dimensional translational connectors from the Modelica.Mechanics.Translational library. They are used to define the 1-dimensional force law acting between the two attachment points. Here, the hydraulic cylinders described in the next section are directly attached. The small two spheres in the icons of the "cyl1f, cyl2f, cyl3f" components indicate that optionally two point masses are taken into account that are attached at defined distances from the attachment
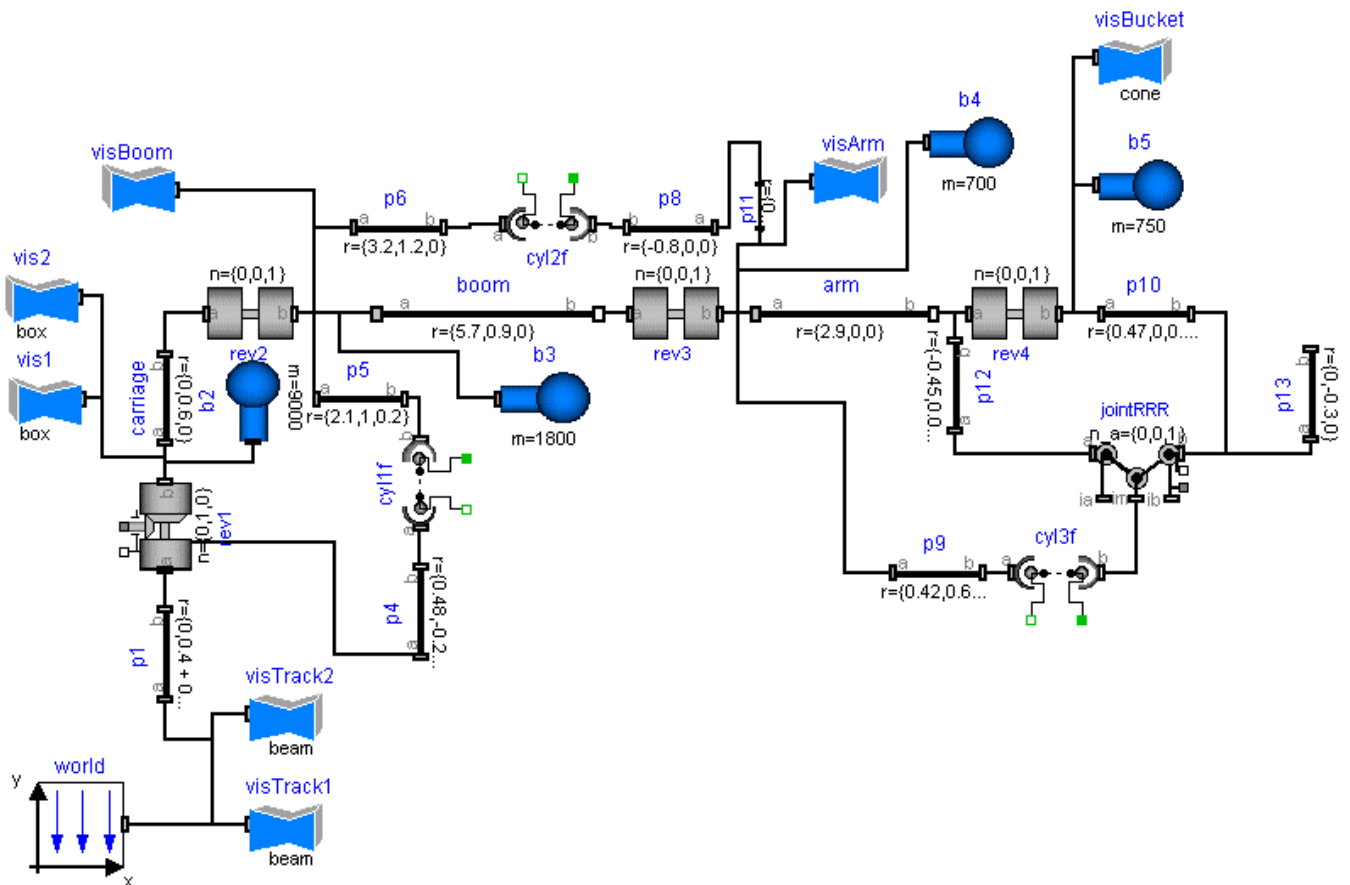

Figure 6 Modelica schematic of mechanical part of excavator

points along the connecting line. This allows to easily model the essential mass properties (mass and center of mass) of the hydraulic cylinders with only a very small computational overhead.

The jointRRR component (see right part of Figure 6) is an assembly element consisting of 3 revolute joints that form together a planar loop when connected to the arm. A picture of this part of an excavator, a zoom in the corresponding Modelica schematic and the animation view is shown in Figure 7. When moving revolute joint "rev4" (= the large red cylinder in the lower part of Figure 7; the small red cylinders characterize the 3 revolute joints of the jointRRR assembly component) the position and orientation of the attachment points of the "left" and "right" revolute joints of the jointRRR component are known. There is a non-linear algebraic loop in the jointRRR component to compute the angles of its three revolute joints given the movement of these attachment points. This non-linear system of equations is solved analytically in the jointRRR object, i.e., in a robust and efficient way. For details see (Otter et. al. 2003).
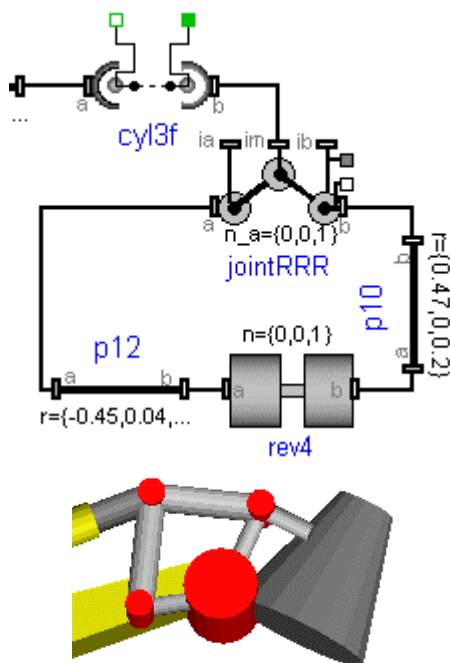

Figure7 Foto, schematic and animation of jointRRR

In a first step, the mechanical part of the excavator is simulated without the hydraulic system to test this part separately. This is performed by attaching translational springs with appropriate spring constants instead of the hydraulic cylinders. After the animation looks fine and the forces and torques in the joints have the expected size, the springs are replaced by the hydraulic system described in the next sections.

All components of the new MultiBody library have "built-in" animation definitions, i.e., animation properties are mostly deduced by default from the given definition of the multi-body system. For example, a rod connecting two revolute joints is by default visualized as cylinder where the diameter d is a fraction of the cylinder length L (d = L/40) which is in turn given by the distance of the two revolute joints. A revolute joint is by default visualized by a red cylinder directed along the axis of rotation of the joint. The default animation (with only a few minor adaptations) of the excavator is shown if Figure 8.
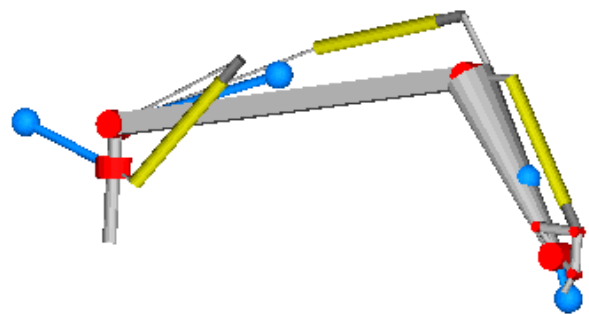

Figure 8 Default animation of excavator

The light blue spheres characterize the center of mass of bodies. The line force elements that visualize the hydraulic cylinders are defined by two cylinders (yellow and grey color) that are moving in each other. As can be seen, the default animation is useful to get, without extra work from the user side, a rough picture of the model that allows to check the most important properties visually, e.g., whether the center of masses or attachment points are at the expected places.

For every component the default animation can be switched off via a Boolean flag. Removing appropriate default animations, such as the "center-of-mass spheres", and adding some components that have pure visual information (all visXXX components in the schematic of Figure 6) gives quickly a nicer animation, as is demonstrated in Figure 9. Also CAD data could be utilized for the animation, but this was not available for the examination of this excavator.
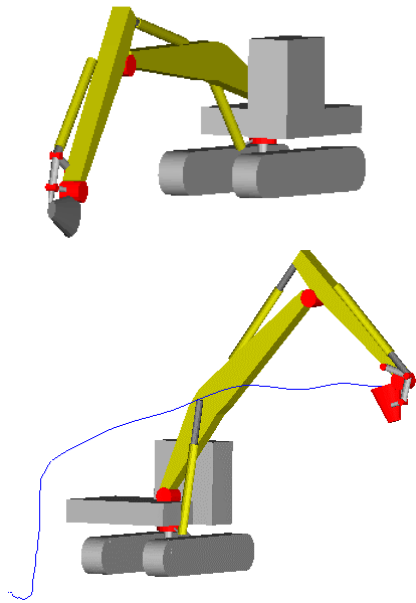
Figure 9 Animation of excavator (start/end position)

6. The Hydraulics Library *HyLib*

The (commercial) Modelica library HyLib (Beater 2000, HyLib 2003) is used to model the pump, metering orifice, load compensator and cylinder of the hydraulic circuit. All these components are standard components for hydraulic circuits and can be obtained from many manufacturers. Models of all of them are contained in HyLib. These mathematical models include both standard textbook models (e. g. Dransfield 1981, Merrit 1967, Viersma 1980) and the most advanced published models that take the behavior of real components into account (Schulz 1979, Will 1968). An example is the general pump model where the output flow is reduced if pressure at the inlet port falls below atmospheric pressure. Numerical properties were also considered when selecting a model (Beater 1999). One point worth mentioning is the fact that all models can be viewed at source code level and are documented by approx. 100 references from easily available literature.

After opening the library, the main window is displayed (Figure 10). A double click on the "pumps" icon opens the selection for all components that are needed to originate or end an oil flow (Figure 11). For the problem at hand, a hydraulic flow source with internal leakage and externally commanded flow rate is used. Similarly the needed models for the valves, cylinders and other components are chosen.

All components are modeled hierarchically. Starting with a definition of a connector – a port were the oil enters or leaves the component –
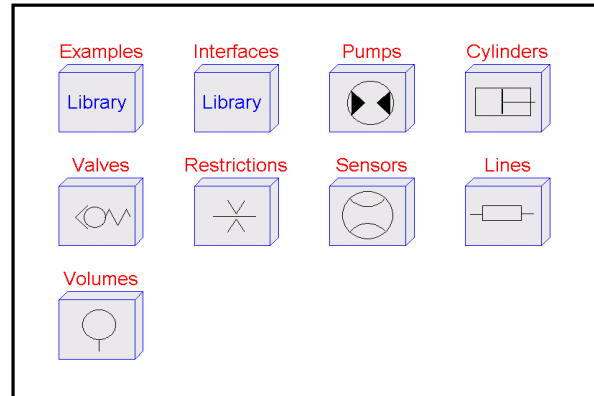

Figure 10 Overview of hydraulics library HyLib

a template for components with two ports is written. This can be inherited for ideal models, e.g., a laminar resistance or a pressure relief valve. While it usually makes sense to use textual input for these basic models most of the main library models were programmed graphically, i.e., composed from basic library models using the graphical user interface. Figure12 gives an example of graphical programming. All mentioned components were chosen from the library and then graphically connected.
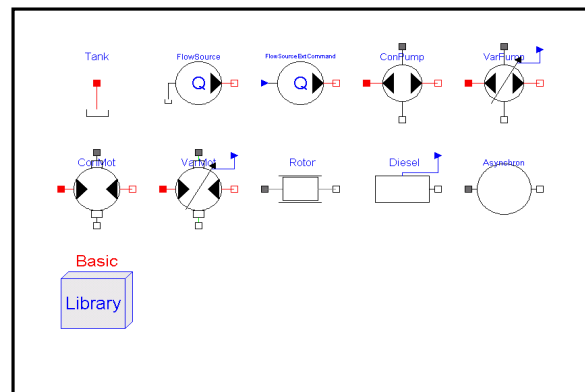

Figure 11 Pump models in HyLib

7. Library Components in Hydraulics Circuit

The composition diagram in Figure 12 shows the graphically composed hydraulics part of the excavator model. The sub models are chosen from the appropriate libraries, connected and the parameters input. Note that the cylinders and the motor from HyLib can be simply connected to the also shown components of the MultiBody library. The input signals, i.e., the reference signals of the driver of the excavator, are given by tables, specifying the diameter of the metering orifice, i.e. the reference value for the flow rate. From the mechanical part
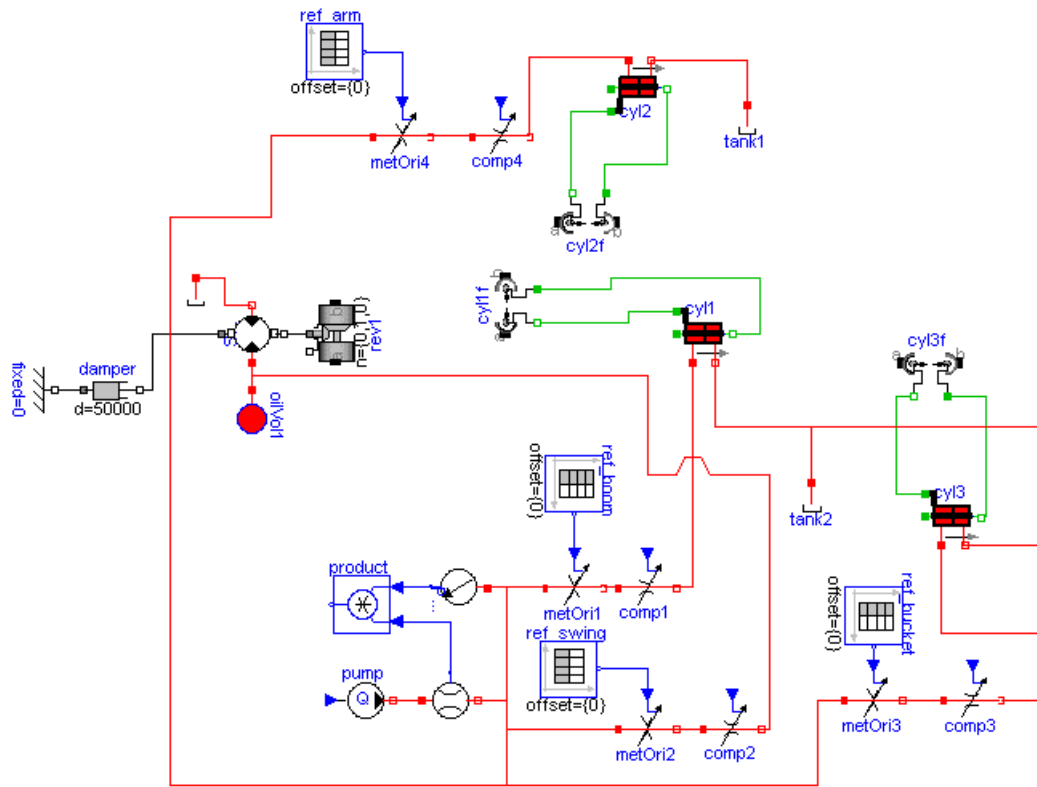
Figure 12 Modelica schematic of hydraulic part of excavator

of the excavator only the components are shown in Figure 12 that are directly coupled with hydraulic elements, such as line force elements to which the hydraulic cylinders are attached.

8. Model of LS Control

For this study the following approach is chosen: Model the mechanics of the excavator, the cylinders and to a certain extent the pump and metering valves in detail because only the parameters of the components will be changed, the general structure is fixed. This means that the diameter of the bucket cylinder may be changed but there will be exactly one cylinder working as shown in Figure 1. That is different for the rest of the hydraulic system. In this paper a Load Sensing system, or LS system for short, using one pump is shown but there are other concepts that have to be evaluated during an initial design phase. For instance the use of two pumps, or a separate pump for the swing.

The hydraulic control system can be set up using meshed control loops. As there is (almost) no way to implement phase shifting behavior in purely hydraulic control systems the following generic LS system uses only proportional controllers.

A detailed model based on actual components would be much bigger and is usually not available at the begin of an initial design phase. It

could be built with the components from the hydraulics library but would require a considerable amount of time that is usually not available at the beginning of a project.

In Tables 1 and 2, the implementation of the LS control in form of equations is shown. Usually, it is recommended for Modelica models to either use graphical model decomposition *or* to define the model by equations, but not to mix both descrip-

Table 1 Modelica code for definition for constants, parameters and variables for LS control system

```
// Definition of variables,
// parameters and constants
import SI = Modelica.SIunits;
SI.Pressure delta_p1;
SI.Pressure delta_p2;
SI.Pressure pump_ls;
SI.Pressure pump_ls1;
SI.Pressure pump_ls2;
SI.Pressure dp_ref(start = 15e5,
                   fixed = true);
Boolean pump_q_max;
Boolean pump_p_max(start = false,
                   fixed = true);

parameter Real       k_LS  =  1e-5;
parameter SI.Pressure p_max = 415e5
```

Table 2 Modelica code for LS Controller, see also Fig. 4 and 5

```
  function conductance "Determine conductance of compensators"
    input  SI.Pressure dp;
    output Real        G;
  algorithm
    G := min(1e-8, max(1e-13, 1e-8 - dp*5e-14));
  end conductance
equation   // Set of equations to model the LS controller
  // define pressure differential across the metering orifices
  // for load compensator and documentation purposes
  delta_p1 = if ref_boom.y[1]   <= 0 then pump.port_B.p
                                  else metOri1.port_A.p - metOri1.port_B.p;
  delta_p2 = if ref_swing.y[1]  <= 0 then 0.0
                                  else metOri2.port_A.p - metOri2.port_B.p;
  delta_p3 = if ref_bucket.y[1] <= 0 then pump.port_B.p
                                  else metOri3.port_A.p - metOri3.port_B.p;
  delta_p4 = if ref_arm.y[1]    <= 0 then pump.port_B.p
                                  else metOri4.port_A.p - metOri4.port_B.p;

  // calculate load pressure for pump controller
  pump_ls1 = if ref_boom.y[1]   <= 0 then pump.port_B.p
                                  else metOri1.port_A.p - comp1.port_B.p;
  pump_ls2 = if ref_swing.y[1]  <= 0 then pump.port_B.p
                                  else metOri2.port_A.p - comp2.port_B.p;
  pump_ls3 = if ref_bucket.y[1] <= 0 then pump.port_B.p
                                  else metOri3.port_A.p - comp3.port_B.p;
  pump_ls4 = if ref_arm.y[1]    <= 0 then pump.port_B.p
                                  else metOri4.port_A.p - comp4.port_B.p;
  pump_ls  = min([pump_ls1, pump_ls2, pump_ls3, pump_ls4);

  // define Boolean state for pump controller
  pump_q_max = k_LS*(15e5 - pump_ls) > 8e-3;

  // set Boolean state if max. pump pressure is reached (with hysteresis)
  pump_p_max = pump.port_B.p > p_max or
               pre(pump_p_max) and pump.port_B.p > 0.95*p_max;

  // calculate command signal for pump
  pump.inPort.signal[1] = if pump_p_max then
                   min(7.5e-3, 7.5e-3 + k_LS*1e-2*(p_max - pump.port_B.p))
               else if pump_q_max then 7.5e-3 else (k_LS*(15e5 - pump_ls));

  // modify reference signal if maximum pump flow rate is exceeded
  dp_ref = if pump_q_max and not pump_p_max then pump_ls else 15e5;

  // calculate conductances of pressure compensators
  comp1.inPort.signal[1] = conductance(delta_p1 - dp_ref);
  comp2.inPort.signal[1] = conductance(delta_p2 - dp_ref);
  comp3.inPort.signal[1] = conductance(delta_p3 - dp_ref);
  comp4.inPort.signal[1] = conductance(delta_p4 - dp_ref);
```

tion forms on the same model level. For the LS system this is different because it has 17 input signals and 5 output signals. One might built one block with 17 inputs and 5 outputs and connect them to the hydraulic circuit. However, in this case it seems more understandable to provide the equations directly on the same level as the hydraulic

circuit above and access the input and output signals directly. For example, ”metOri1.port_A.p” used in table 2 is the measured pressure at port_A of the metering orifice metOri1. The calculated values of the LS controller, e.g., the pump flow rate “pump.inPort.signal[1] = ...” is the signal at the

filled blue rectangle of the "pump" component, see Figure 12).

The strong point of Modelica is that a seamless integration of the 3-dimensional mechanical library, the hydraulics library and the non standard, and therefore in no library available, model of the control system is easily done. The library components can be graphically connected in the object diagram and the text based model can access all needed variables.

9. Some Simulation Results

The complete model was built using the Modelica modeling and simulation environment Dymola (Dymola 2003), translated, compiled and simulated for 5 s. The simulation time was 17 s using the DASSL integrator with a relative tolerance of 10^{-6} on a 1.8 GHz notebook, i.e., about 3.4 times slower as real-time. The animation feature in Dymola makes it possible to view the movements in an almost realistic way which helps to explain the results also to non-experts, see Figure 9.

Figure 13 gives the reference signals for the three cylinders and the swing, the pump flow rate and pressure. From t = 1.1 s until 1.7 s and from t = 3.6 s until 4.0 s the pump delivers the maximum flow rate. From t = 3.1 s until 3.6 s the maximum allowed pressure is reached.
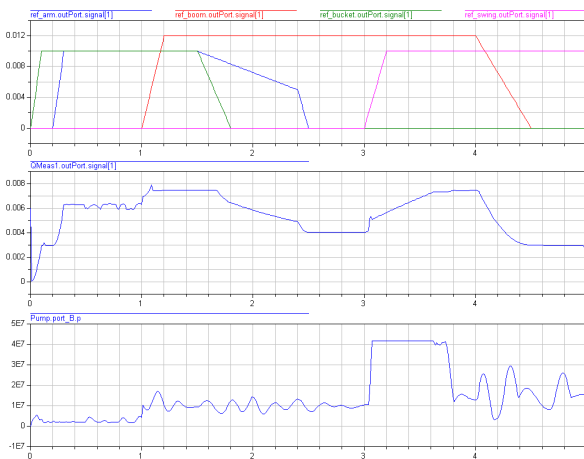

Figure 13 Reference, pump flow rate and pressure

Figure 14 gives the position of the boom and the bucket cylinders and the swing angle. It can be seen that there is no significant change in the piston movement if another movement starts or ends. The control system reduces the couplings between the consumers which are very severe for simple throttling control.
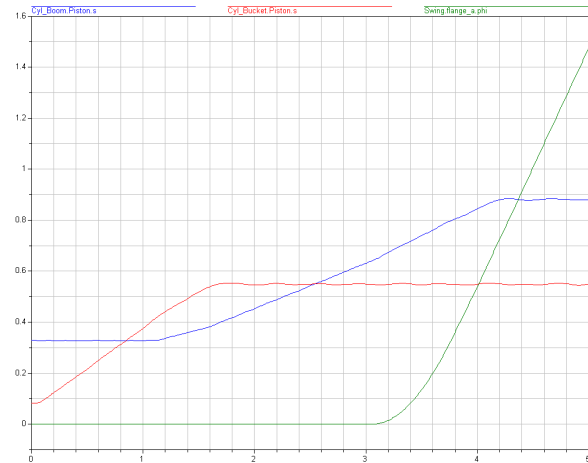

Figure 14 Boom (blue) and bucket (red) piston position and swing angle (green)

Figure 15 shows the operation of the bucket cylinder. The top figure shows the reference trajectory, i. e. the opening of the directional valve. The middle figure shows the conductance of the compensators. With the exception of two spikes it is open from t = 0 s until t = 1 s. This means that in that interval the pump pressure is commanded by that bucket cylinder. After t = 1 s the boom cylinder requires a considerably higher pressure and the bucket compensator therefore increases the resistance (smaller conductance). The bottom figure shows that the flow rate control works fine. Even though there is a severe disturbance (high pump pressure after t = 1 s due to the boom) the commanded flow rate is fed with a small error to the bucket cylinder.
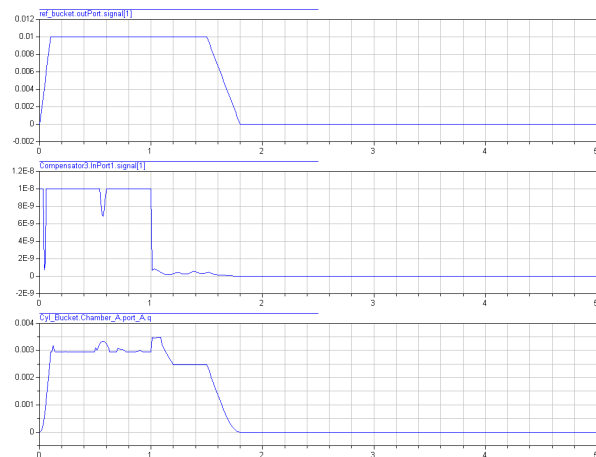

Figure 15 Operation of bucket cylinder

10. Conclusion

For the evaluation of different hydraulic circuits a dynamic model of an excavator was built. It consists of a detailed model of the 3 dimensional mechanics of the carriage, including boom, arm and bucket and the standard hydraulic components like pump or cylinder. The control system was not modeled on a component basis but the system was described by a set of nonlinear equations.

The system was modeled using the Modelica MultiBody library, the hydraulics library Hylib and a set of application specific equations. With the tool Dymola the system could be build and tested in a short time and it was possible to calculate the required trajectories for evaluation of the control system.

The animation feature in Dymola makes it possible to view the movements in an almost realistic way which helps to explain the results also to non experts.

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