EFFICIENT COLLABORATIVE MODELLING AND SIMULATION WITH APPLICATION TO WHEEL LOADER DESIGN

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Abstract

Technical systems are becoming increasingly integrated, partly because of the intensive use of software due to demands for energy efficiency, performance and customizability. This leads to complicated interactions among the sub-systems during operation. The dynamic behaviour of such a system is hard to predict since every sub-system needs to be taken into account. Also, the sub-systems often differ in characteristics between engineering domains, and engineers therefore need to collaborate to make the prediction. A validated model is needed to predict how a change to a system will affect its behaviour. The paper investigates how the modelling, simulation and validation processes can be organized in the described case where several engineers from different disciplines are involved. The application studied is a wheel loader that is complex and represents a large family of machines. In the resulting approach, teams of engineers from the different disciplines create one general-purpose model, each team using the most appropriate modelling environment. The system simulation is realized through coupled simulation, where accurate results are achieved by connecting the simulation environments by so-called bilateral delay lines.

Keywords: collaborative, multi-domain, hydraulics, multi-body dynamics, coupled simulation, bilateral delay lines

1 Introduction

Early in 1998, Volvo Construction Equipment, Volvo Trucks and the Department of Mechanical Engineering at Linköping University, Sweden, launched a joint project on simulation of complex systems. The aim was to find a suitable approach for collaborative system-level design of off-road machinery by means of modelling and simulation as well as to produce a validated model of a specific machine. The model was to be used for, among other things, analysis of fuel consumption and comfort issues. A wheel loader was chosen to represent machines such as excavators, haulers and similar, where hydraulics, mechanics and electronics form a whole of integrated, complex sub-systems. The approach should, however, be applicable to most physical systems where the sub-systems are complex, belong to different engineering/scientific disciplines, and are highly integrated.

The general motives for making use of simulation in loader design are familiar to all designers. There are today stricter legal requirements on exhaust emissions and sound, and tougher customer demands regarding performance and handling. This leads to machinery with lighter mechanical structures, more integrated and adaptive functions by means of software, energy efficient actuation and less power available from the diesel engine in certain situations. The systems are designed to operate closer to their maximum capacity and the tolerance for error then becomes smaller. Trial and error design methods are no longer applicable since the optimum solution space is smaller and both shorter development times and lower development costs are demanded on top of the former requirements.

The test case studied in this paper is the so called short loading cycle, where granular material is moved by the loader from a pile to a nearby truck, dumper or hauler. This case is the toughest when it comes to the amount of transients and interaction in the system. As is described in (Filla and Palmberg, 2003), when loading, the bucket first has to penetrate the pile and this requires traction force. This is achieved by transferring torque from the diesel engine via a torque converter, transmission, axles and the wheels to the ground. A typical sequence for filling the bucket is then to break material by tilting the bucket backwards a bit, lifting

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some and increasing the traction force. The lift and tilt functions require engine power to be transferred through the hydraulic pumps, cylinders and loading unit. These two different paths are competing for the limited engine power during the loading procedure. In designing the loader, the power paths therefore need to be balanced throughout the loading procedure. The design parameters such as pump sizes and link geometry are chosen so that the balance is kept not only in static but also in transient situations, the normal case. Simulation is necessary in order to find this balance unless large resources are to be spent on physical testing.

The paper initially describes the loader itself and its sub-systems. After that follows a discussion on appropriate modelling approach, the modelling and measurement of the hydraulics in particular, a necessary simulation technique used in a new way and finally conclusions. The loading procedure during measurements as well as in simulation is shown below. This validated loading procedure simulation, which is one of the main results of the paper, would not have been possible without the modelling, measurement and simulation approaches utilized.

Fig. 1: *Loading procedure; reality and simulation, the upper illustration is from Volvo Construction Equipment, Sweden*

2 Related Work

There are a few papers describing the joint modelling of powertrains, fluid power components and systems and vehicle dynamics. One of them is (Tiller et al, 2000). The focus in these papers is on the problem to be solved and the mathematics of the models, rather than on the collaborative process itself for producing a validated model. In an industrial setting the process is an important issue. Papers which do describe the process have not enough detailed models and thus do not need to deal with many of the practical problems that this paper brings forward and solves.

The paper treats coupled simulation. In order for this to be stable and accurate, special measures need to be taken. In the context of involving conventional simulation environments, there are few papers written on how to reduce the simulation error introduced by the solver decoupling. Some of these methods, such as post-stabilization (Cline, 2003), demand that the state variables can be reset, something which is time consuming and not always possible due to the simulation environment working principles. In the paper, a known simulation technique that does not have this constraint is successfully applied to the coupled simulation of the loader. Regularization (Knorrenschild, 1992) is also possible to implement with conventional environments, but results in a stiff problem that is time-consuming to solve.

3 The Loader

The engine is a 12 liter, 6-cylinder straight turbocharged diesel engine. The driveline includes a single-stage torque converter and an automatic power-shift transmission.

The hydraulic system is load-sensing. This means that the pumps control the pressure at a constant difference above the highest load pressure. Two variable piston pumps provide all hydraulics with oil, as is shown in Fig. 2. Pump P1 only provides the working hydraulics with oil through the control valve whereas pump P2 supplies the central valve. The central valve directs the flow from pump P2 to the steering and any excess flow to the working hydraulics. Pump P3 is for cooling fan and brakes. These are some of functions that have been ignored in the modelling work and in the figure, as is discussed later.

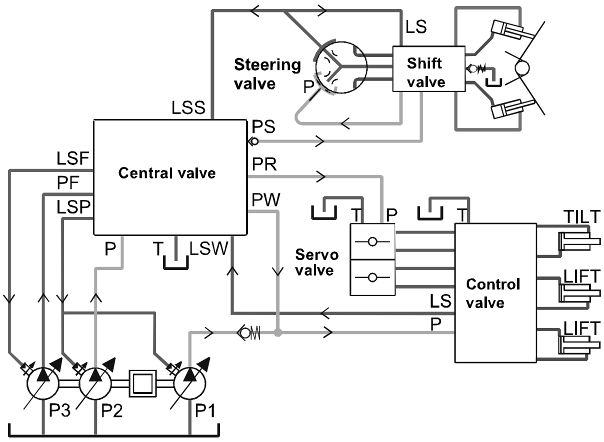

Fig. 2: *Working- and steering hydraulics. The brake- and cooling functions are not shown, P denotes high pressure, T is tank and LS indicates load-sensing path*

The loader has articulated steering with double-acting cylinders. A shift valve connects the outer chamber of the steering cylinder to high pressure when the pressure exceeds a certain level. The choice of steering cylinder depends on the steering direction. The steering is controlled either by joystick or steering wheel, of which the steering wheel solution is depicted in the figure.

There are a number of functions that have not been considered in the modelling and testing work of the hydraulics. The main reasons for this are that these functions are not of primary interest and require modest power in comparison with steering- and working functions. The functions are cooling, brakes, boom suspension and additional hydraulic cylinders. Boom suspension is used to dampen chassis oscillations.

4 Collaborative Modelling

Traditionally, a number of models of the same system are created manually to study one or more aspects at a time. In the context of wheel loader design, this could be a model with a detailed description of the hydraulic sub-system together with simplified powertrain and chassis. This way, each model can be made simple and the aspects under study are not obscured by details. The modeller is in this situation at the first peak of model usefulness, shown in Fig. 3.

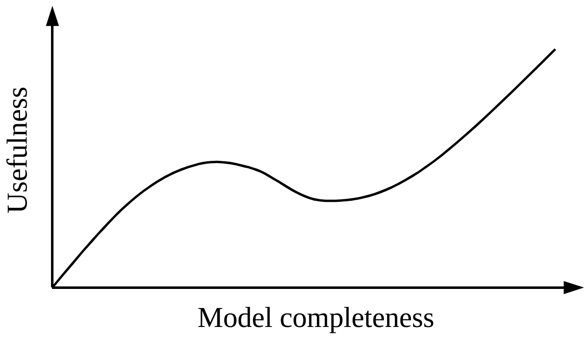

Fig. 3: *The usefulness of a model as a function of the size,or completeness of it, compared to the physical system*

As the model is made more detailed, the details begin to obscure the important results. A model that is even more complete, however, begins to resemble the actual system modelled and can be regarded as a general test bench and be used in the same way as tests are performed on the physical system. Once again, for the wheel loader, this would be a model that contains detailed descriptions of all sub-systems. So, what approach is more suitable in wheel loader design, several specialized models or one general?

In (Brooks and Tobias, 1996) it is pointed out that large, detailed models are difficult to comprehend and demand resources, at times excessive, to build. A simple model can, however, also be difficult to comprehend, in terms of validity range, for example, since it is intended for a narrow purpose, as is also mentioned in (Brooks and Tobias, 1996). The comprehension of the detailed models can also be improved by decomposing them into pieces that are created and understood by individual modellers. The work is minimized if redundant work is kept to a minimum, which is the case with multi-purpose models. These general models can be constrained by disabling certain parts by parameter settings to reduce the amount of phenomena included in the simulation. The models then come close to the special-purpose models in terms of simplicity. Finally, future model reduction, as shown in (Louca and Stein, 1999) will provide the performance that today can be an obstacle when dealing with detailed models.

So, it can be more efficient to make use of one general detailed model instead of several simple models. This is especially true in wheel loader design, where the machines are about the same from one version to another. When this is the case, the models can be reused and a consistent approach is the result. This was the approach adopted in the loader project.

In Fig. 4, a system decomposition for the wheel loader is shown, where the large model is made up of several domain-specific parts to reduce complexity. The interfacing quantities necessary to perform a simulation are chosen such that they do not need to be differentiated in the computations. This operation causes numerical difficulties. With this decomposition, three teams of engineers from different disciplines can cooperate in modelling the system. Cooperation is necessary for these multi-domain systems where one person cannot have all the knowledge needed.

For each domain there exist a number of specialized modelling environments that the team members in each domain are familiar with in terms of vocabulary, modelling formalism etc. If, as here, one system model is created that is made up of sub-models for each main domain, then the teams responsible for corresponding sub-systems can use modelling environments that are intuitive to them.

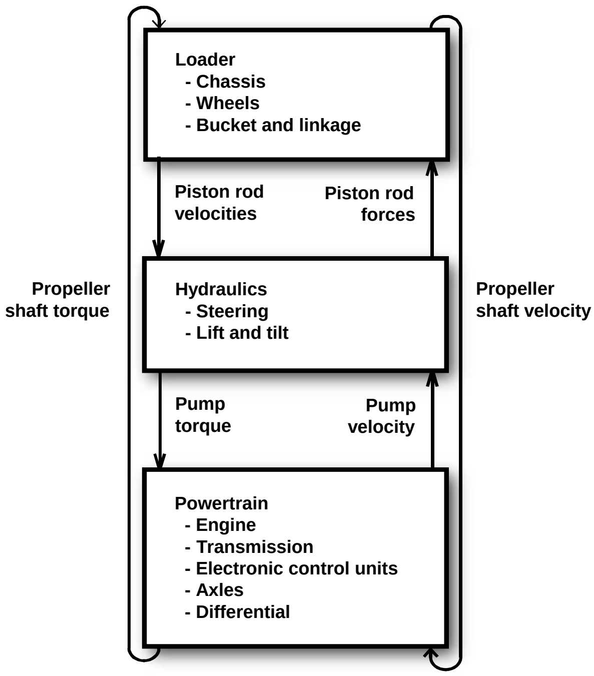

Fig. 4: *Modular general-purpose model*

One analyst was made responsible for the powertain in the loader project. Matlab/Simulink was chosen for this model since an earlier model already existed in this environment. In the same manner one analyst was made responsible for the sub-system of chassis, lifting unit and wheels, which already existed for an older loader in Adams. There was no model for the hydraulics. This sub-system was assigned to one person who made use of Hopsan, a tool specialized in hydraulic systems, described in (Larsson et al, 2002). The corresponding models are shown below.

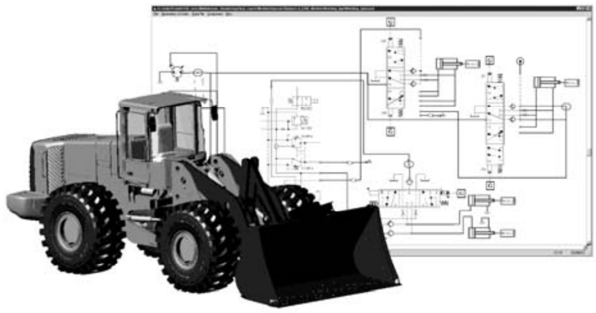

Fig. 5: *Models of chassis and hydraulics in Adams and Hopsan respectively*

5 Modelling and Validation

Measurements are needed in order to create reliable models. A complicating factor with a loader is the large amount of components (such as pumps) involved. Individual component test setups, where former measurements did not exist, would have been impossible in terms of time and money. Instead, the quantities measured were chosen such that the behaviour of each component could be identified and isolated during complete system operation. This way, the components are also subjected to realistic boundary conditions during measurements, as compared to when run in test rigs.

The static parts of the flows of the two main pumps were measured using sensors of low bandwidth, placed in extended pipes to achieve laminar flow. Pressures were measured for all steering and working hydraulics cylinder chambers, for the outlet ports of the pumps, the maximum load pressure feedback, the pilot pressures from the steering joystick that act upon the manoeuvre valves and the brake pressure. The torques in both forward and rear propeller shafts were measured, 12 accelerometers were placed at strategic positions on the chassis and angles were measured for steering, lift and tilt functions. Furthermore, existing transducers on the machine were used for measuring engine speed, turbo pressure, vehicle velocity, cooling fan speed and engagement of transmission clutches. Gas pedal position and throttle control position were also measured.

The loader was filmed during some measurements, but what would have been valuable is a film camera in the cabin that captures the movements and comments of the driver. If the film is synchronized with the measurements, the film can be used for education to illustrate how pressures etc change in response to the driver input. The film also provides information about human-machine interaction and the outside environment that is difficult to catch otherwise. Examples of the latter could be a hole in the ground, slipping wheels etc.

The measurements can apart from model validation be used in themselves to see how power is split dynamically among the different functions. With this knowledge it is possible to automate this distribution in future loaders and refine present powertrains and other sub-systems.

5.1 Modelling of Gravel and Loader

The load in terms of a gravel pile was modelled and validated. It contains damping, shearing forces, weight and the gravel can flow continuous into a bucket. The model is described in (Slättengren and Ericsson, 2000). In validating the model, pre-recorded angles from measurements were used for the lift and tilt functions as inputs to a mechanical model where the computed forces in the cylinders were compared with forces computed from measured pressure differences. The results for the forces in the lift cylinder are shown in Fig. 6 where the bucket is driven into the gravel, lifted and then emptied.

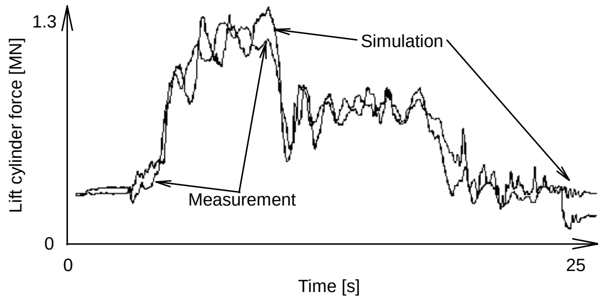

Fig. 6: *Comparison between simulation results and measurements on lift cylinder forces in loading gravel, the solid line is the simulation.*

The powertrain model was validated using test cases where a constant gas pedal position was used as input while the vehicle accelerated to top speed. The damping in the torque converter and the losses in the transmission needed adjustment in the models. The chassis and tires were analysed using modal analysis for adjustment of bushing- and tire characteristics.

5.2 Modelling of Hydraulics

Loader manufacturers are often system integrators in the sense that they purchase components from sub-contractors, tune them, and integrate them to a system. This is especially true for the hydraulics system. For each machine or valve, it is important that the model can be treated as the real thing, that every spring or orifice can be exchanged in order to alter the characteristics. This demands that the components are modelled using physical parameters rather than general transfer function parameters such as resonance frequency and damping. This is illustrated below in the case of the pumps.

The pump controllers are equipped as shown in Fig 7. The main control piston is indicated with a “1” and its preloaded spring with a “2”. The four-way valve “3” directs flow to the main piston in such a way that the pump pressure is kept at a certain level above the load pressure. The load pressure acts on the right side of this valve as it has been copied by the valve “4”. The valve “5” limits the fed back load pressure to a pre-set maximum level.

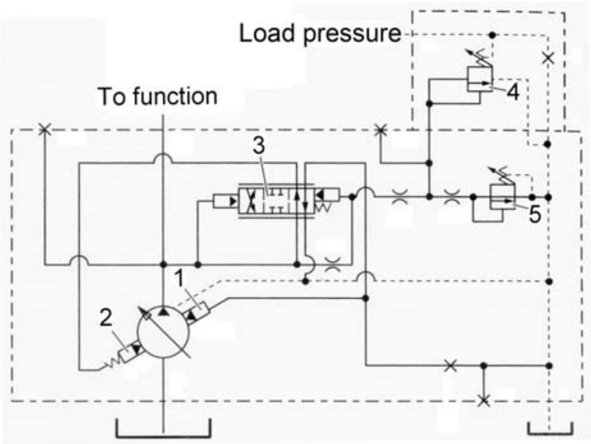

Fig. 7: *Pump and its controller*

The corresponding model is shown in Fig. 8. The same numbers are used here as in the former picture. Apart from the valves and pistons shown, the model includes volumetric and mechanical efficiency models for the pump. These are based on measurements performed at Volvo and have pressure level and rotational speed as inputs. The dynamic properties, such as time needed for pressure build-up and pressure decline, were validated towards the full vehicle measurements.

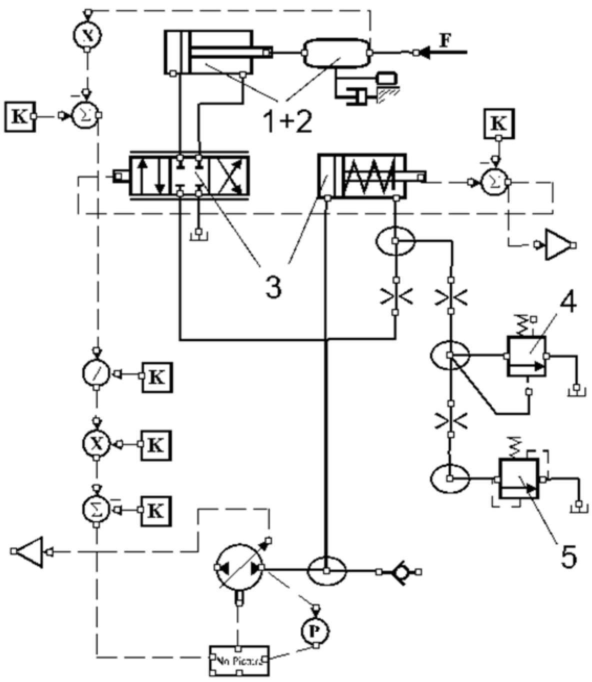

Fig. 8: *Pump and controller model*

The lift/lowering spool section of the directional control valve is shown in Fig. 10 in the situation where lowering takes place at the same time as the bucket is tilted inwards. In order for the pump to build up pressure during lowering to supply the tilt operation, the servo pressure for tilt in is applied on top of the right load-holding poppet. This makes the sensed load pressure increase and thus the supplied pump pressure. Furthermore, the main spool has an extra position for float operation where both load ports are connected directly to each other. This spool position is reached by increasing the servo pressure to such a level that it overcomes the spring pretension of the float-position piston. The difference between final simulation model and measurements is shown in Fig. 9. There, the bucket is lifted and lowered at half and full speed. The error is mostly due to the difficulty in modelling the flow forces acing on the spool, as mentioned later.

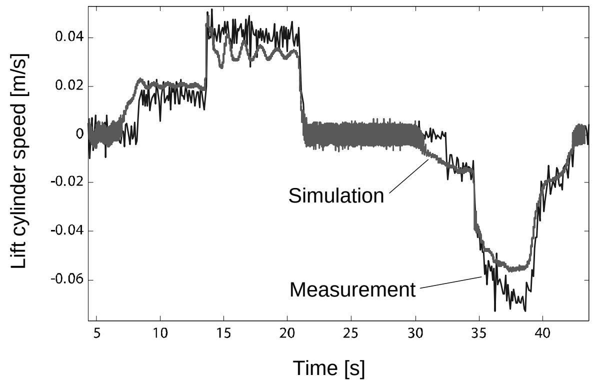

Fig. 9: *Comparison between simulation results (“slower curve”) and measurements on the lift cylinder speed*

The valve manufacturer had measured the forces acting upon the spool for different pressure difference levels as a function of spool position in static conditions. This had been done for the four possible flow paths between load ports, pump and tank and each measurement included the flow. The forces include force caused by the flow itself as well as the springs that center the spool. To find the total force acting on the spool during lowering, as an example, the forces from flow paths pump to load port B and load port A to tank must be added somehow.

Both forces act in the left direction in Fig. 10 and are summed. After that, one set of spring forces are removed so that the springs are not taken account for twice. The spring forces are simply computed from the position.

In simulation, the measured flow forces are chosen from a map with spool position and pressure difference as input. The forces act on the spool component part of the larger control valve model which computes flow as a function of pressure difference and opening area. This area is determined by spool position and spool geometry.

The load-holding poppet valves and control valves are modelled as first-order systems with time constants determined by sizes of the surrounding orifices. This modelling technique is used to improve numerical stability and thus simulation performance. The spool is on the other hand modelled as a mass-damper system.

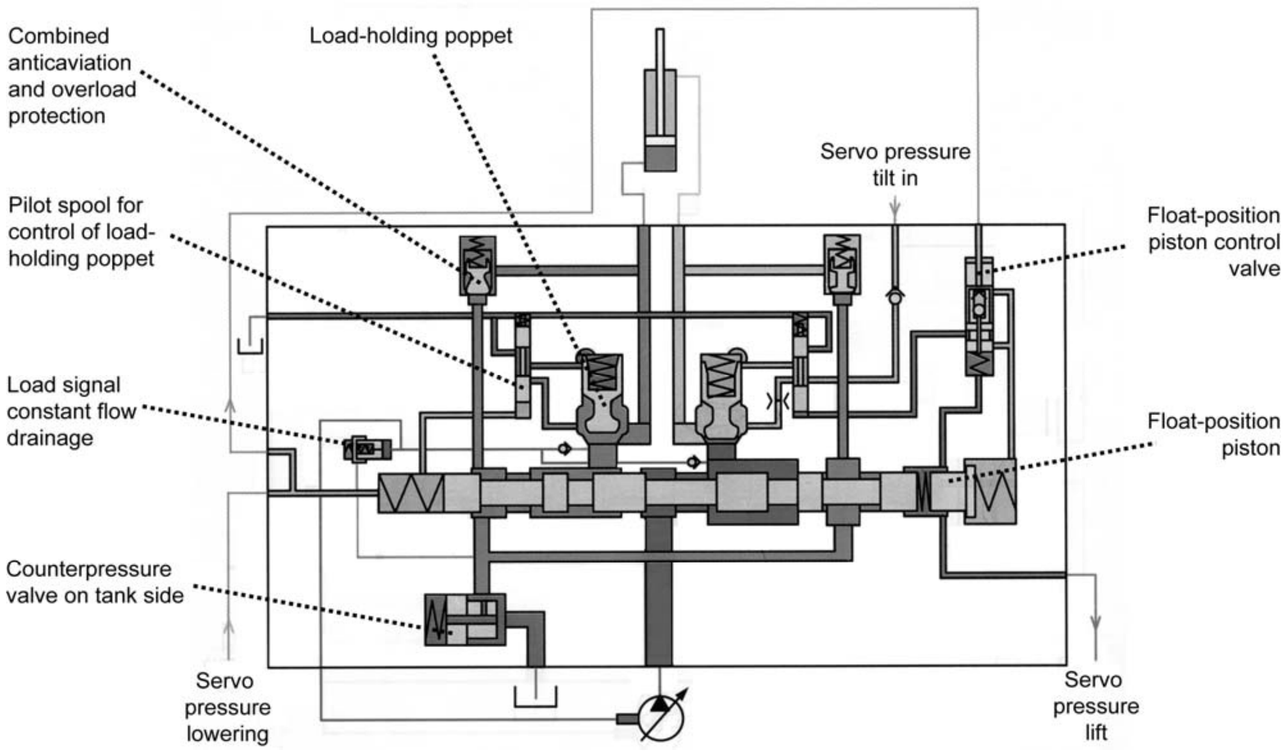

Fig. 10: *The lift section of the control valve*

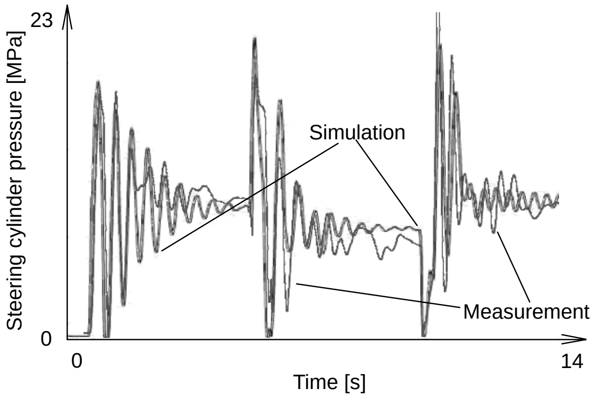

Fig. 11: *Comparison between simulation results and measurements on steering cylinder pressure, the solid line is the simulation*

The steering hydraulics was modelled and validated in a master thesis work. Some results are shown in Fig. 11. The test case was such that the steering wheel was turned 90 degrees quickly twice in a row in the same direction and then back in the same manner. The dynamical response is dependent on tires, the chassis, the whole hydraulic supply and the steering- and shift valves. This figure illustrates the difficulty in validating such a complex system as this is. It is possible to reach the same resonance frequencies and correct timing. But the static levels are dependent on mechanical friction and flow restriction in several components simultaneously. It can therefore be hard to distinguish how much each component contributes to the phenomena. But as a reward, after the effort in creating a modular model, each component can be exchanged in future loaders, keeping most of the old model intact.

6 Simulation

The system model is the result of integrating the various sub-models in one of two possible ways. The first is to integrate the models into one common model representation, such as an equation-based modelling language and simulate this model in any simulation environment supporting the modelling language. The second one is to couple the modelling environments so that their numerical solvers can perform a joint simulation in which interfacing variables are exchanged at a limited number of time points through simulation. Both approaches are difficult to achieve when ordinary modelling environments are utilized with their inherent constraints. There is however research being performed in both areas which is shortly referred to below, starting with model integration.

6.1 Model Integration

Equation-based modelling languages such as Modelica (Fritzson and Engelson, 1998) and VHDL-AMS (Christen and Bakalar, 1999) do not contain solver-specific information and the models must thus be compiled into executable code. If the modelling environments supported these languages, a user would be able to use the most appropriate modelling environment with regard to user interface etc. The combined model of the models created in different modelling environments could then be simulated in one simulation environment, which often offers many benefits compared to performing a coupled simulation involving several solvers.

In (Larsson and Krus, 2003), the problem that modelling languages are not supported by more than a few simulation environments is addressed by leaving the final simulation code generation in the necessary model compiling process open to the user. What mainly hinders the model integration approach is, however, that some models are not possible to separate from the modelling environment used. This is the case when a certain numerical solver is needed or when the models are not accessible. This will hopefully change in the future. For now, coupled simulation can be applied in those situations where model integration is not possible.

6.2 Coupled Simulation

In a contact between two parts of a physical system, the "information" of flow and pressure, in the hydraulic case, flows continuously in time in both directions. If the two parts are separated by a fluid volume of a certain length in space, the information will still propagate continuously but with a time delay between the two ends determined by the speed of sound and the volume length. This phenomena is illustrated in Fig. 12, where $q(t)$ is the incoming flow, $p(t)$ is pressure and $c(t)$ is the information flow. The indexes 1 and 2 indicate the two parts that are connected.

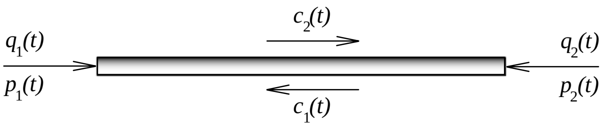

Fig. 12: *A fluid volume as an information carrier*

If the volume has no length, there will be no time delay. This case is difficult two simulate if the two parts have been modelled and are computed in different solvers – coupled simulation. In that case, the computations performed in any of the solvers depend on the variables of the other solvers at the same time instant. The only way of achieving a convergent solution is to iterate among the solvers while keeping the simulation time constant. This can seldom be achieved with conventional simulation environments, since the simulation time in each solver is increased after each computation.

But if the volume does have a length, then the information needed by a solver from the other solvers is known (since it is old) and no iteration is needed. This is exploited in the method of bilateral delay lines, first described in (Auslander, 1968). The equations describing these lines are explored below and brought into the context of coupled simulation.

If an infinite number of inductance and capacitance elements are connected in series, and the relations between pressure and flow, in the hydraulic case, are derived, the following expressions are found.

$$p_1(t) = Z_c q_1(t) + p_2(t-T) + Z_c q_2(t-T) \tag{1}$$

$$p_2(t) = Z_c q_2(t) + p_1(t-T) + Z_c q_1(t-T) \tag{2}$$

In Eq. 1 and 2, p_1 and p_2 are the pressures at the different ends of the line and q_1 and q_2 are the incoming flows, as shown in Fig. 12. The time it takes for information to travel from one end to the other is denoted T. The parameter Z_c is T over C where C is the capacitance of the line, which in this case is volume over bulk modulus.

Let us now denote the old information from node 1 with c_2 and from node 2 with c_1. These "waves" of information are shown in Fig. 12 and are expressed below.

$$c_1(t) = p_2(t-T) + Z_c q_2(t-T) \tag{3}$$

$$c_2(t) = p_1(t-T) + Z_c q_1(t-T) \tag{4}$$

Equation 1 and 2 then become

$$p_1(t) = Z_c q_1(t) + c_1(t) \tag{5}$$

$$p_2(t) = Z_c q_2(t) + c_2(t) \tag{6}$$

So, if two simulation environments are connected, the pressure and flow in one of them can be computed given the pressure and flow from the other the time T earlier. The procedure is shown in Fig. 13. In each environment, computation of pressure and flow is performed at discrete time points, indicated with small dots. The large dots indicate the regular exchange of pressure and flow through lists of c_1 and c_2. These waves need to be inter- or extrapolated w r t time in order to correspond to the right time point. The communication interval determines the time delay of the delay line and thus its length. A long communication interval corresponds to a long line and vice versa. The normal situation is that the communication is longer than it should be compared to the physical system. The line simulated is then longer than in reality and this show as a too large inertia.

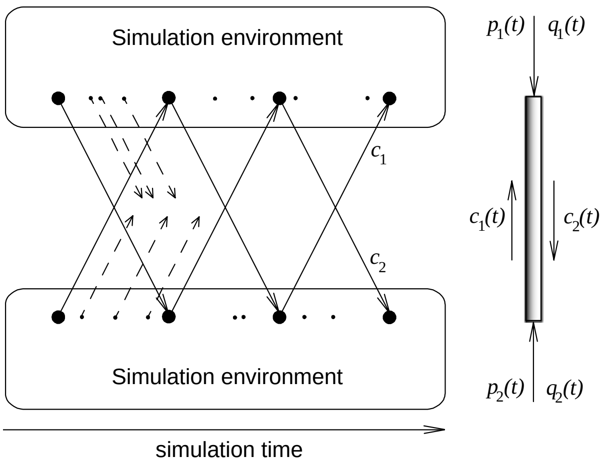

Fig. 13: *Coupled simulation using delay lines*

In the loader project, the mechanical model resided in the Adams simulation environment and the hydraulic system model resided in Hopsan. The interface was in the form of hydraulic pistons where the piston rod was in Adams and the cylinder volume in Hopsan. The volume acted as a delay line. Matlab/Simulink was used to connect ADAMS and Hopsan and to simulate the powertrain. These tools communicated the variables towards Simulink using socket communication. Without the delay lines, the simulation did not converge, but with them, almost any communication interval could be used among the tools. With the delay lines, a communication interval of 1 ms was needed for “good enough” accuracy. The full model runs at a speed of about 100 times slower than real time on a Pentium III at 600 MHz.

In this case, the volume changed in size during simulation and this needs to be considered in the delay line computation as is shown in (Jansson et al, 1991). Delay lines have been used earlier in coupled simulation, but then within simulation environments specialized in this simulation method (Jansson et al, 1991; Pollmeier, 1996). A comparison to other methods in terms of stability and accuracy is performed in (Larsson, 2004).

7 Conclusions

A consistent engineering approach to modelling, simulation and measurement has been discussed where only one system model exists, where several special-purpose simulation environments are used both for modelling and simulation and where the whole system is measured in one piece. The method of bilateral delay lines is evaluated in the coupled simulation of the loader. The delay line method made the simulation possible and increased the simulation performance.

Since the work has resulted in a validated system model, the ideas in the project have been applied to a complex application, and engineers and students have done most of the work, the authors are confident in saying that industry can adopt the approach already today with only moderate difficulty.

Acknowledgements

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