Institutet för Tillämpad Hydraulik

Technical Report

Document No.	ETH1-02
Title	Hydraulic modeling of a reach stacker load handling system using SimulationX software
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Date	2011-09-05

Hydraulic modeling of a reach stacker load handling system using SimulationX software

Abstract

A conventional hydraulic reach stacker load handling system has been modeled in the SimulationX software. The objective of the simulation exercise was to obtain a functional model of the load handling system accommodated for energy system analysis. The simulation model comprises an MBS model of the boom assembly and a hydraulic system of the boom lift and boom extension functions. Since a hydraulic system model of this size easily can become very complex with plausible calculation problems and poor usability, the model has intentionally been kept as simple as possible. The report contains a comprehensive simulation model description and reasonable simulation results for a 90 seconds load handling sequence. A number of assumptions and definitions for the model are discussed concerning simulation accuracy. The model needs to be verified by comparing simulation results to measurement data.

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1 Background

The ‘Energy efficient hydraulic systems with energy regeneration’ research project is an ITH post-graduate project supervised at Luleå University of Technology. The project is financed by the European Regional Development Fund together with BAE Systems Hägglunds, the County of Örnsköldsvik and the County Administration of Västernorrland. The research project will increase the level of competence within the area of energy efficient hydraulics in general and especially potential and kinetic energy regeneration in heavy equipment hydraulic load handling systems. Heavy equipment here refers to motor-driven vehicles specially designed for executing load handling tasks such as wheel loaders, excavators, container trucks, forklift trucks, mobile cranes etc.

The project comprises computer simulations where an existing heavy equipment hydraulic load handling system is compared to alternative hydraulic and electro-hydraulic system solutions in order to map out the most energy efficient solution for different system conditions. Electro-hydraulic systems here refer to hydraulic systems where parts of the hydraulics are replaced with electrical components as for example electrical machines and batteries.

So fare a literature study has been done with focus on the product and system solution state of the art concerning energy efficient heavy equipment. Also, a simulation software evaluation has been carried out resulting in the selection of the SimulationX software from ITI GmbH. As a first SimulationX exercise a 3D multi-body system (MBS) model of the driving and load handling functions of a reach stacker container truck was modeled [1]. Now, a conventional hydraulic load handling system of the same reach stacker container truck has been modeled in SimulationX.

2 Objectives

The objective of the simulation exercise is to build a model of a conventional hydraulic reach stacker load handling system. The simulation model is to be accommodated for energy system analysis. The simulation model will comprise an MBS model of the boom assembly and a hydraulic system of the boom lift and boom extension functions. Other separate parts of the hydraulic system concerning attachment functions, braking, steering, cooling etcetera will not be comprised. Energy losses in diesel engine and transmission will not be considered.

3 Materials and methods

3.1 Simulation software

The 3D multi-body system model is built in the SimulationX computer software, which is a multi-domain system simulation tool. In addition to the 3D multi-body system library, there are standard libraries for hydraulics, power transmission, electrical drives, thermodynamics, electrics and controls etc.

3.2 Simulation object

The simulation object is a reach stacker container truck which handles 20 and 40 feet containers with a maximum lift capacity of approximately 45 ton. The simulation model is based on dimensions and technical data of the Kalmar DRF450 reach stacker manufactured by Cargotec (see Figure 1).

Figure 1. Kalmar DRF450 reach stacker [2].

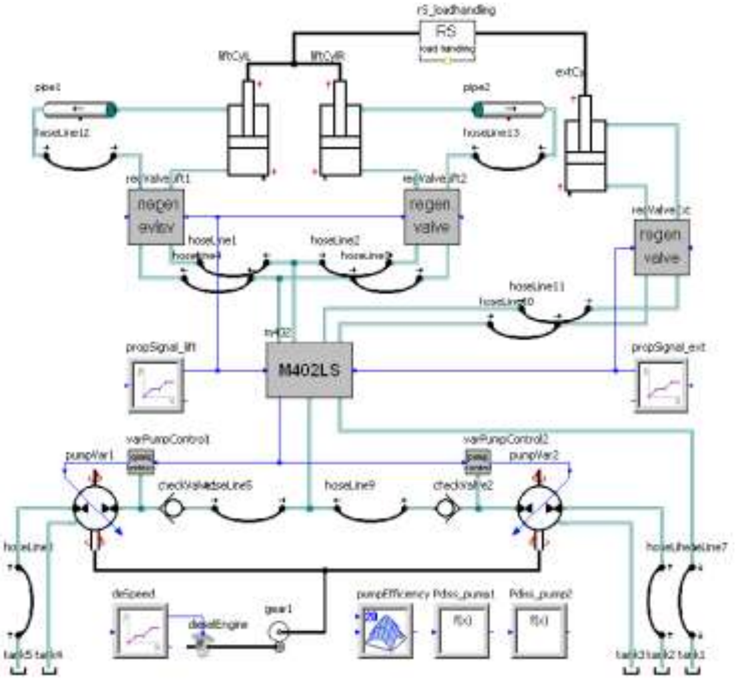


Figure 2. Hydraulic load handling simulation model.

3.3 Model description

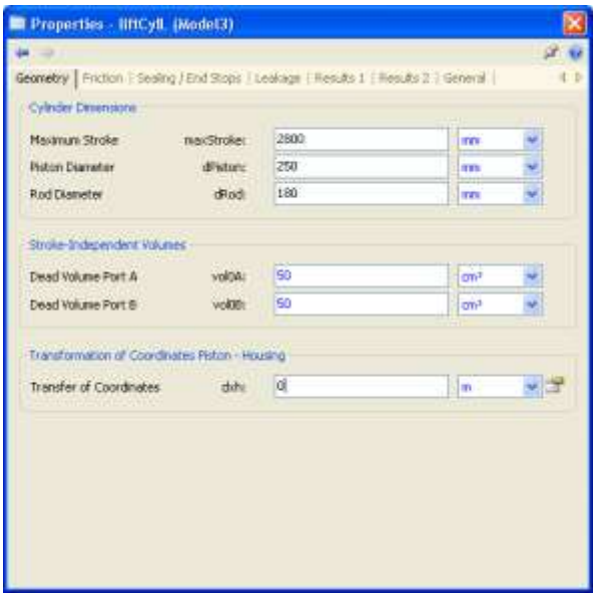
The hydraulic system managing the boom lift and boom extension functions of the reach stacker is a so called load sensing (LS) system. This means that the displacements of the variable pumps are controlled in order to match the highest pressure demand. The simulation model can be seen in Figure 2 and consists of standard SimulationX element types such as variable pumps, differential cylinders and valves, as well as a number of element types specially assembled for this system: the M402 directional control valve, the variable pump control block and the regenerative valve block. In addition to the hydraulic components there is also a boom assembly multi body system (MBS) connected to lift and extension cylinders. Main input parameters to the model are:

- Diesel engine speed [rpm]
- Container weight [ton]
- Directional control valve spool positions (lift and extension functions) [mm]

A model specification can be seen in Appendix 3 and all components are further explained in the following chapters.

3.3.1 Lift and extension cylinders

The lift and extension cylinders are modeled in similar way by the differential cylinder element type. Geometry data like maximum stroke, piston diameter and rod diameter are set in the geometry tab of the property window (see Figure 3). The dead volumes at port A and B are set to default values. In the friction tab seen in Figure 4 a mechanical efficiency of 97% are defined. In the sealing / end stops tab the elastic sealing are inactivated and a rigid end stop is selected (see Figure 5). Finally, in the leakage tab no internal or external leakages are considered (Figure 6).

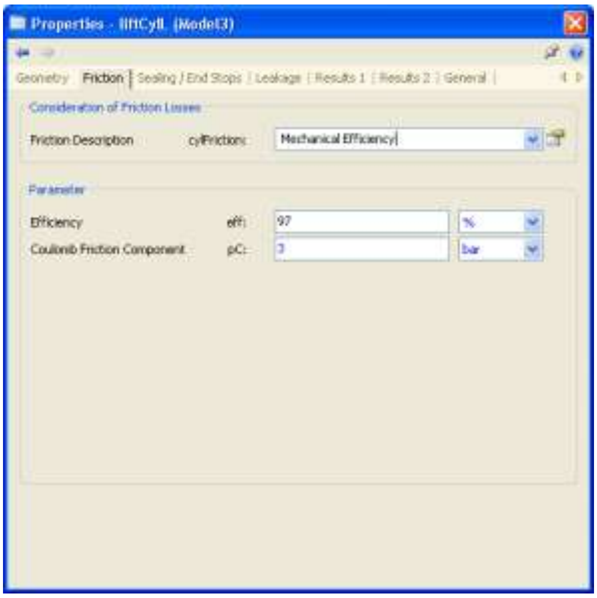


Cylinder Dimensions
Maximum Stroke maxStroke: 2800 mm
Piston Diameter dPiston: 250 mm
Rod Diameter dRod: 180 mm

Stroke-Independent Volumes
Dead Volume Port A vol0A: 50 cm^3
Dead Volume Port B vol0B: 50 cm^3

Transformation of Coordinates Piston - Housing
Transfer of Coordinates dxh: 0 m

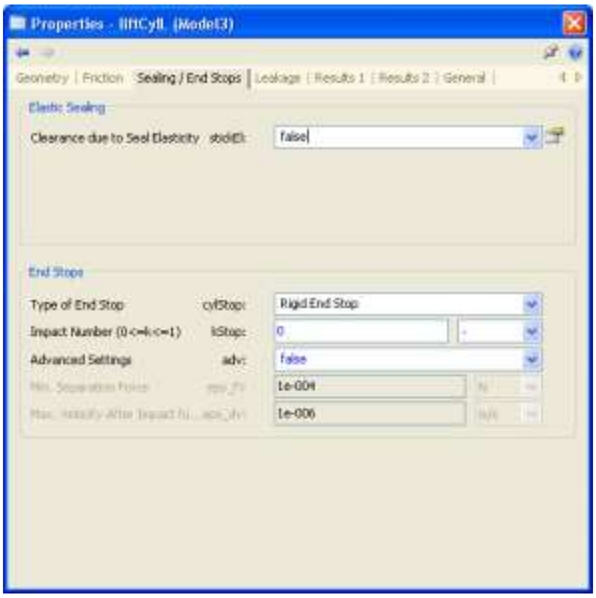
Figure 3. The geometry tab of the differential cylinder element type



Consideration of Friction Losses
Friction Description cylFriction: Mechanical Efficiency

Parameter
Efficiency eff: 97 %
Coulomb Friction Component pC: 3 bar

Figure 4. The friction tab of the differential cylinder element type



Elastic Sealing
Clearance due to Seal Elasticity stickEl: false

End Stops
Type of End Stop cylStop: Rigid End Stop
Impact Number (0<=k<=1) kStop: 0 -
Advanced Settings adv: false
Min. Separation Force sep_F: 1e-004 N
Max. Velocity After Impact fo... vel_dv: 1e-006 m/s

Figure 5. The sealing / end stops tab of the differential cylinder element type

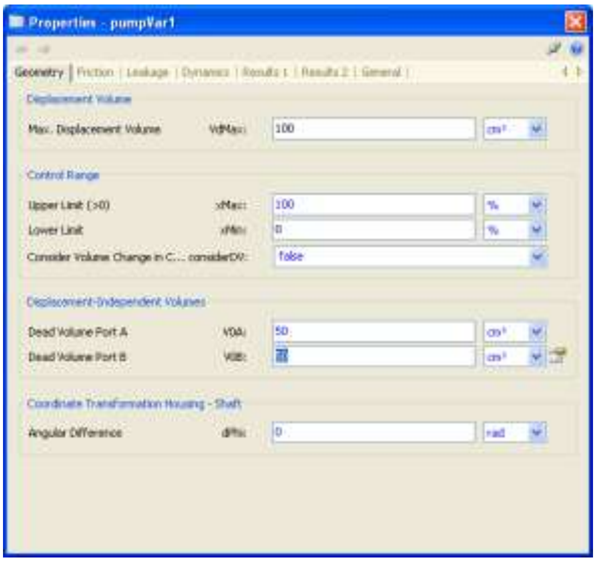
Internal Leakage
Consider Internal Leakage intLeakage: false

External Leakage
Consider External Leakage extLeakage: false

Figure 6. The leakage tab of the differential cylinder element type

3.3.2 Variable pumps

The two variable displacement pumps are connected to power take-offs at the gear box. In the simulation model the gear box is defined by the 1:1.1 ratio 'gear1' elements and the diesel engine is defined by the 'dieselEngine' rotational preset element. This gives a correct rotational speed input to the pumps based on a given diesel engine speed but doesn't consider any energy losses in diesel engine or gear box.



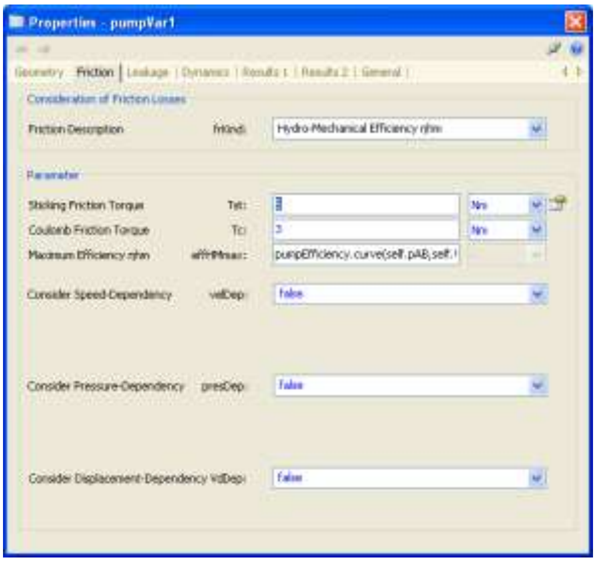
Displacement Volume
Max. Displacement Volume VdMax: 100 cm³

Control Range
Upper Limit (>0) xMax: 100 %
Lower Limit xMin: 0 %
Consider Volume Change in C... considerDV: false

Displacement-Independent Volumes
Dead Volume Port A V0A: 50 cm³
Dead Volume Port B V0B: [illegible] cm³

Coordinate Transformation Housing - Shaft
Angular Difference dPhi: 0 rad

Figure 7. The geometry tab of a variable pump.



Consideration of Friction Losses
Friction Description frKind: Hydro-Mechanical Efficiency ηhm

Parameter
Sticking Friction Torque Tst: [illegible] Nm
Coulomb Friction Torque Tc: 3 Nm
Maximum Efficiency ηhm effHMmax: pumpEfficiency.curve(self.pAB,self.
Consider Speed-Dependency velDep: false
Consider Pressure-Dependency presDep: false
Consider Displacement-Dependency VdDep: false

Figure 8. The friction tab of a variable pump.

In the geometry tab of the pump property window (see Figure 7) the maximum displacement volume has been defined and the lower control limit set to zero, all other parameters has been unchanged from default values. There is a number of different ways of defining both hydro-mechanical and volumetric losses. In the friction tab (see Figure 8) the hydro-mechanical efficiency has been defined from the separate 2D map element 'pumpEfficiency' seen in Figure 9. This map is however actually describing the total pump efficiency and therefore no volumetric losses in the leakage tab are considered (see also discussion chapter 6.1). The dynamic of the pump are considered in the separate variable pump control element (see chapter 3.3.3) and hence the built in pump dynamics is inactivated in the dynamics tab.

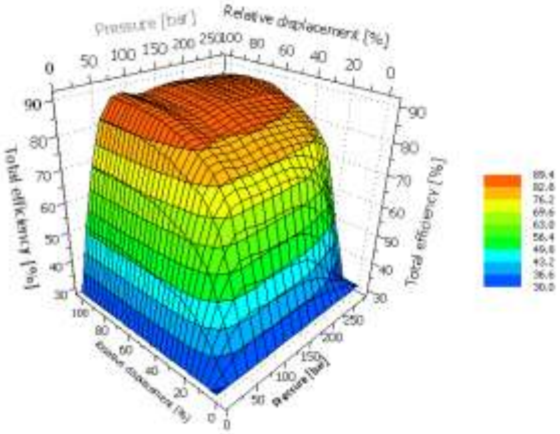


Figure 9. The pump efficiency is defined by the 'pumpEfficiency' 2D map element.

It has been discovered that some compression losses in the pump are not taken into account by the software when calculating the pump losses. Therefore, for the energy analysis, the total power dissipation of the pump is also calculated from the effective volume flow and pressure drop in the separate 'Pdiss_pump1' element.

3.3.3 Variable pump control

The variable pump control element type seen in Figure 10 has been built in order to control the displacement of the variable pumps based on the LS (load sensing) signal from the directional control valve. By selecting 'Load sensing' in the property window the maximum pump pressure and standby pressure can be set (see Figure 11). The actual load pressure is determined from the LS signal from the directional valve and added to the standby pressure. The 'maxPressure' function block is limiting the pressure if exceeding maximum pressure limit and the signal is then compared to the actual pump pressure. The final step is a PID-controller module with anti-windup function. The output signal is then sent to the pump in order to control the displacement volume. The element type specification can be seen in Appendix 7.

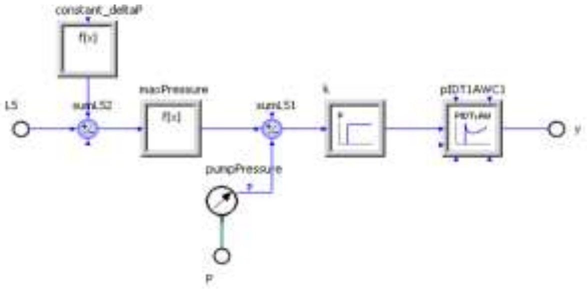
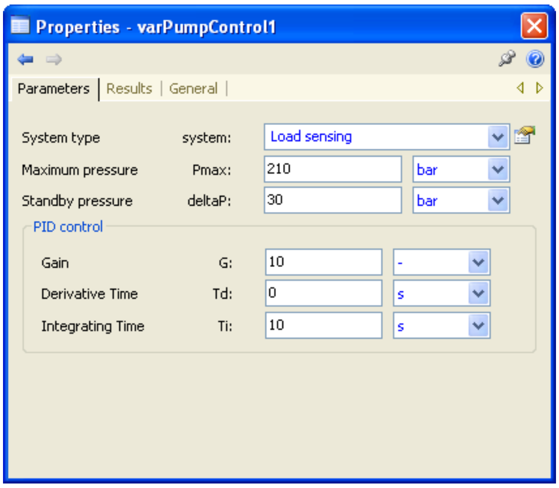


Figure 10. The structure of the variable pump control element type.



System type system: Load sensing
Maximum pressure Pmax: 210 bar
Standby pressure deltaP: 30 bar
PID control
Gain G: 10 -
Derivative Time Td: 0 s
Integrating Time Ti: 10 s

Figure 11. The variable pump control property window.

3.3.4 M402 directional control valve

The M402 directional control valve element type seen in Figure 12 comprises two 4/3 proportional valves, a counter pressure valve and anti-cavitation valves similar to the Parker Hannifin M402LS mobile directional control valve seen in Figure 13. It has a LS signal output which could simulate both electrical and hydraulic LS signals.

The parameters I tab in M402 property window (see Figure 14) enables the user to configure the 4/3 proportional valves. In our model valve dynamics are not considered since the idea is to define the actual spool positions as simulation input parameters (e.g. from measurements). The flow vs. spool stroke characteristic is defined at 20 bar pressure drop either as a setup function in a table or as a linear dependence (see valve 1 and 2 respectively in Figure 14). By defining the stroke length in millimeter the absolute stroke length can be monitored during simulation. One can choose whether to get a LS signal at plus stroke and minus stroke respectively; and the LS lap can be defined for both valves. The 'dynamik' function block is a simple transfer function which defines some dynamics in the LS signal, helping the simulation calculations by smoothing out sudden pressure changes. In the parameters II tab (see Figure 15) one can configure the counter pressure valve and the anti-cavitation valve settings. The counter pressure valve has a small bypass throttle securing the refilling of the tank line. The element type specification can be seen in Appendix 5.

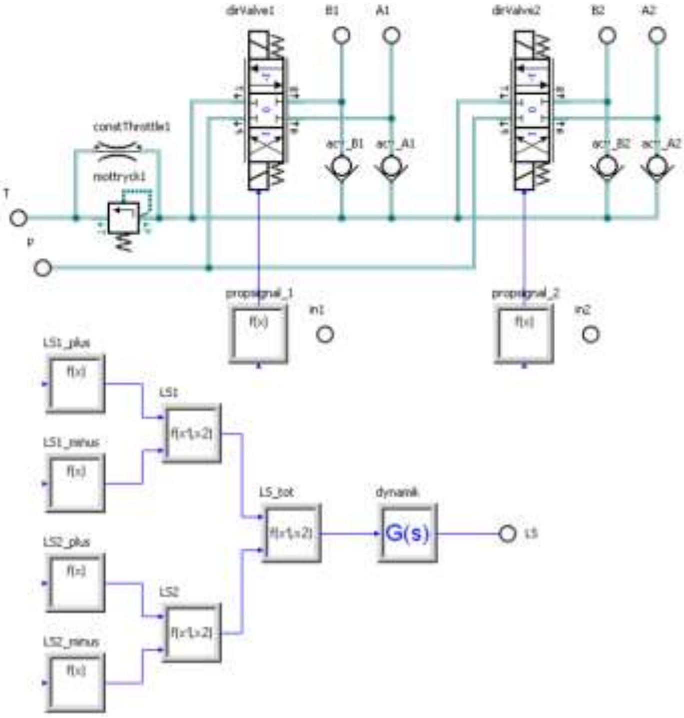
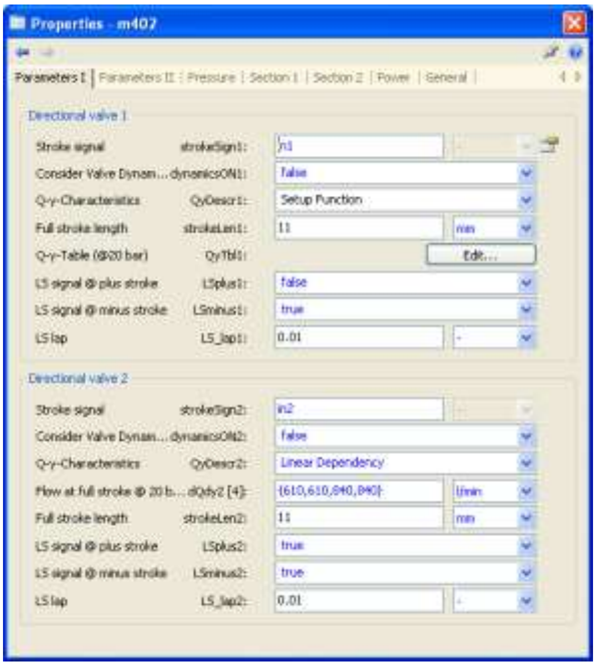


Figure 12. The structure of the M402 directional control valve element type.

Figure 13. The Parker Hannifin M402LS mobile directional control valve [3].



Properties - m402

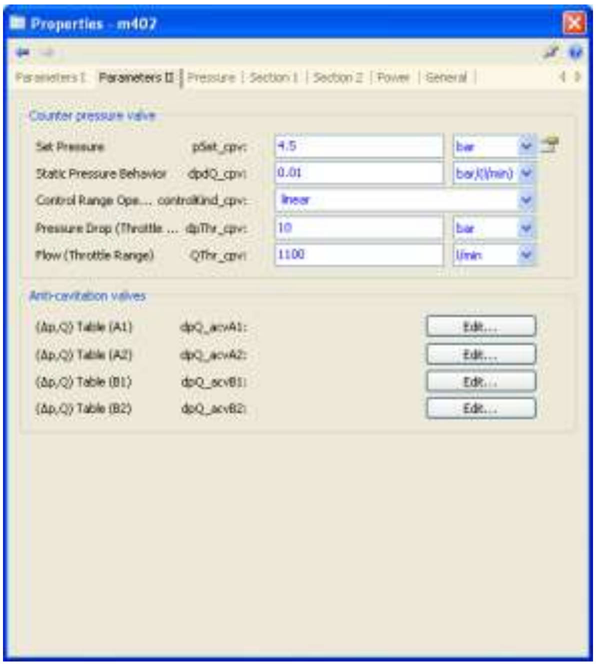
Directional valve 1

Stroke signal strokeSign1: in1
Consider Valve Dynam... dynamicsON1: false
Q-y-Characteristics QyDescr1: Setup Function
Full stroke length strokeLen1: 11 mm
Q-y-Table (@20 bar) QyTbl1: Edit...
LS signal @ plus stroke LSplus1: false
LS signal @ minus stroke LSminus1: true
LS lap LS_lap1: 0.01 -

Directional valve 2

Stroke signal strokeSign2: in2
Consider Valve Dynam... dynamicsON2: false
Q-y-Characteristics QyDescr2: Linear Dependency
Flow at full stroke @ 20 b... dQdy2 [4]: {610,610,840,840} l/min
Full stroke length strokeLen2: 11 mm
LS signal @ plus stroke LSplus2: true
LS signal @ minus stroke LSminus2: true
LS lap LS_lap2: 0.01 -

Figure 14. The parameters I tab of the M402 directional control valve element type.



Properties - m402

Counter pressure valve

Set Pressure pSet_cpv: 4.5 bar
Static Pressure Behavior dpdQ_cpv: 0.01 bar/(l/min)
Control Range Ope... controlKind_cpv: linear
Pressure Drop (Throttle ... dpThr_cpv: 10 bar
Flow (Throttle Range) QThr_cpv: 1100 l/min

Anti-cavitation valves

(Δp,Q) Table (A1) dpQ_acvA1: Edit...
(Δp,Q) Table (A2) dpQ_acvA2: Edit...
(Δp,Q) Table (B1) dpQ_acvB1: Edit...
(Δp,Q) Table (B2) dpQ_acvB2: Edit...

Figure 15. The parameters II tab of the M402 directional control valve element type.

3.3.5 Regenerative valve

The regenerative valve element type seen in Figure 16 comprises two throttle valve elements (load holding and regenerative valve) and one spring biased check valve element. The load holding valve ‘lhValve’ is normally closed but opens fully when lowering (same signal as the M402 spool stroke signal) and lifting (when pressure at port VA exceeds the load pressure at Cplus). The regenerative valve ‘regValve’ is normally fully open but closes at the regenerative signal. This enables faster lifting at moderate loads by leading the oil from the cylinder minus side through the spring biased check valve to the cylinder plus side. The property window (see Figure 17) enables the user to configure each valve element. The element type specification can be seen in Appendix 6.

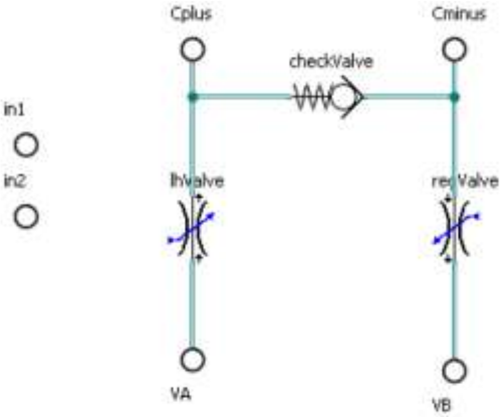
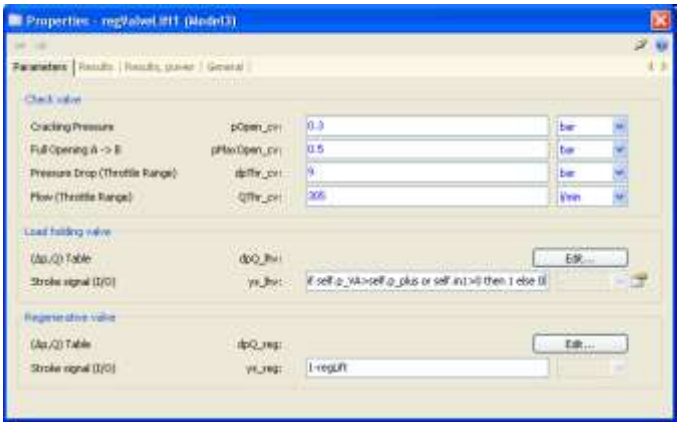


Figure 16. The structure of the regenerative valve element type.



Check valve

Cracking Pressure pOpen_cv: 0.3 bar
Full Opening A -> B pMaxOpen_cv: 0.5 bar
Pressure Drop (Throttle Range) dpThr_cv: 9 bar
Flow (Throttle Range) QThr_cv: 305 l/min

Load holding valve

(Δp,Q) Table dpQ_lhv:
Stroke signal (I/O) ys_lhv: if self.p_VA>self.p_plus or self.in1>0 then 1 else 0

Regenerative valve

(Δp,Q) Table dpQ_reg:
Stroke signal (I/O) ys_reg: 1-regLift

Figure 17. The property window of the regenerative valve element type.

3.3.6 Reach stacker MBS

The reach stacker MBS element type seen in Figure 18 and Figure 19 is build in similar way as the reach stacker load handling MBS element type described earlier in technical report ETH1-01 [1], but has different boom geometries and element masses. The new geometries are obtained simply by importing cad structures of outer boom, inner boom, cylinders etcetera and then adjusting the element displacements. In the initial values tab of the property window (see Figure 20) the container weight and initial boom position is defined. One can also change the friction coefficients of the boom rotational, spreader rotational and boom extension joints (see also discussion chapter 6.2). Available result variables regarding boom motions, power dissipation etcetera can be seen in Figure 21, Figure 22 and Figure 23. The element type specification can be seen in Appendix 4.

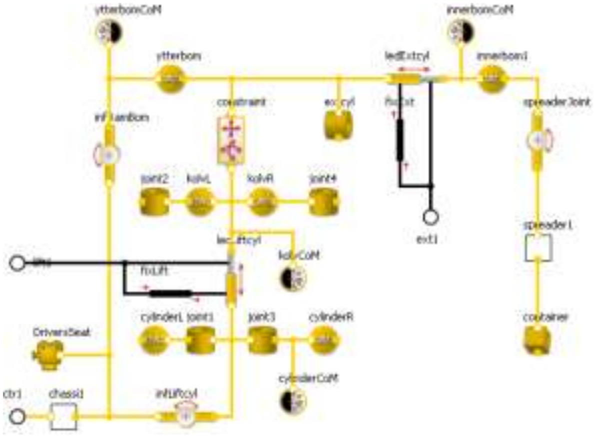


Figure 18. The structure of the reach stacker MBS element type.

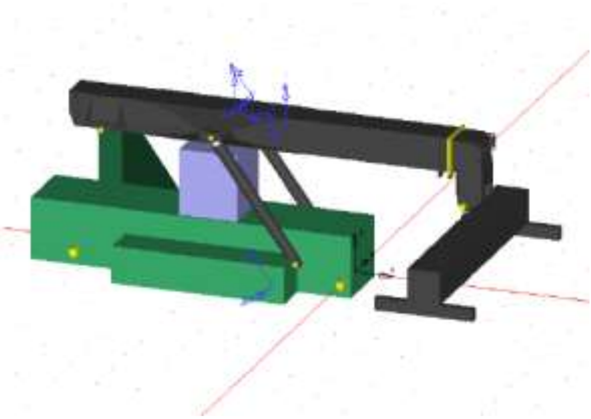
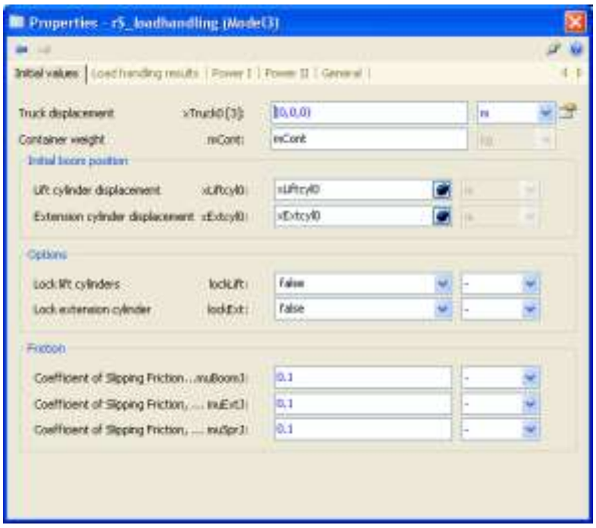


Figure 19. 3D-view of the reach stacker MBS element type.



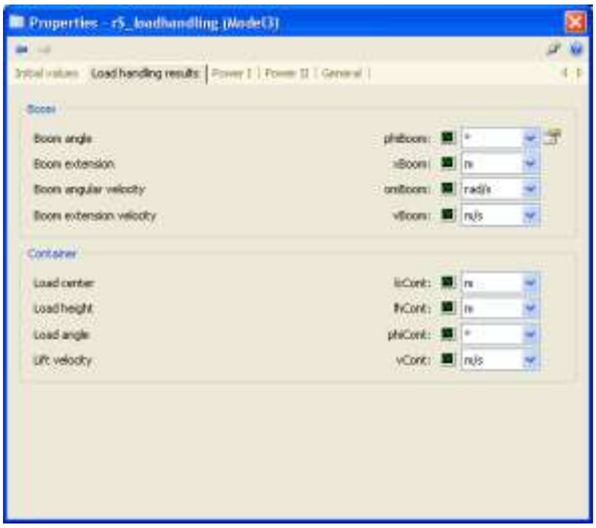
Truck displacement xTruck0[3]: {0,0,0} m
Container weight mCont: mCont kg

Initial boom position
Lift cylinder displacement xLiftcyl0: xLiftcyl0 m
Extension cylinder displacement xExtcyl0: xExtcyl0 m

Options
Lock lift cylinders lockLift: false -
Lock extension cylinder lockExt: false -

Friction
Coefficient of Slipping Friction...muBoom3: 0.1 -
Coefficient of Slipping Friction, ... muExt3: 0.1 -
Coefficient of Slipping Friction, ... muSpr3: 0.1 -

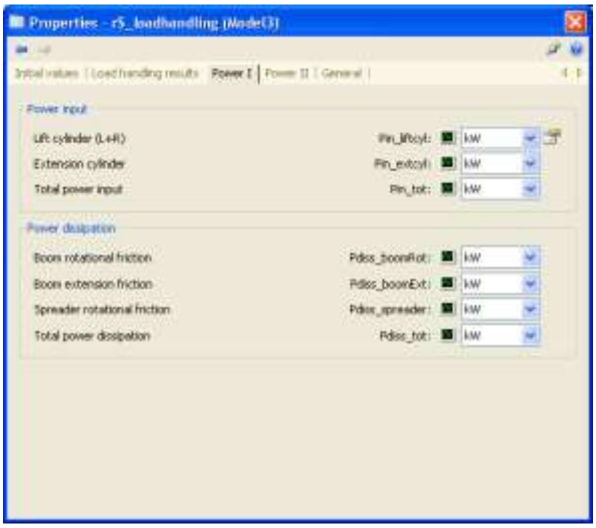
Figure 20. The initial values tab of the reach stacker MBS element type.



Boom
Boom angle phiBoom: °
Boom extension xBoom: m
Boom angular velocity omBoom: rad/s
Boom extension velocity vBoom: m/s

Container
Load center lcCont: m
Load height hCont: m
Load angle phiCont: °
Lift velocity vCont: m/s

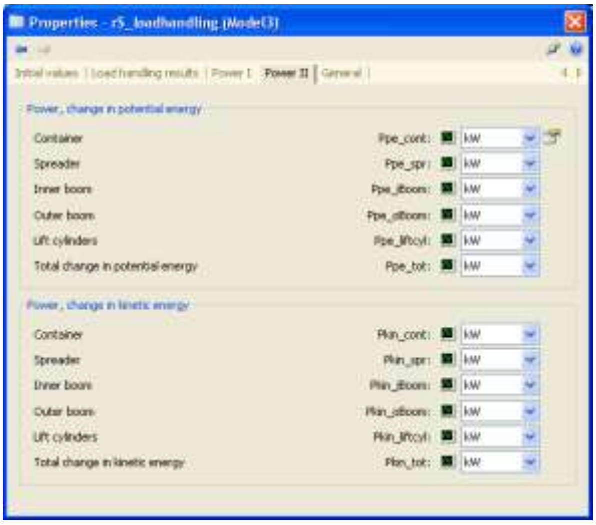
Figure 21. The load handling results tab of the reach stacker MBS element type.



Power input
Lift cylinder (L+R) Pin_liftcyl: kW
Extension cylinder Pin_extcyl: kW
Total power input Pin_tot: kW

Power dissipation
Boom rotational friction Pdiss_boomRot: kW
Boom extension friction Pdiss_boomExt: kW
Spreader rotational friction Pdiss_spreader: kW
Total power dissipation Pdiss_tot: kW

Figure 22. The power I results tab of the reach stacker MBS element type.



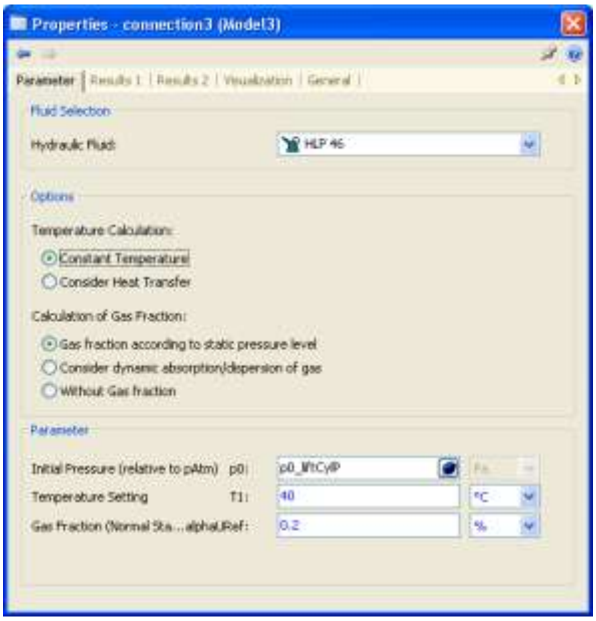
Power, change in potential energy
Container Ppe_cont: kW
Spreader Ppe_spr: kW
Inner boom Ppe_iBoom: kW
Outer boom Ppe_oBoom: kW
Lift cylinders Ppe_liftcyl: kW
Total change in potential energy Ppe_tot: kW

Power, change in kinetic energy
Container Pkin_cont: kW
Spreader Pkin_spr: kW
Inner boom Pkin_iBoom: kW
Outer boom Pkin_oBoom: kW
Lift cylinders Pkin_liftcyl: kW
Total change in kinetic energy Pkin_tot: kW

Figure 23. The power II results tab of the reach stacker MBS element type.

3.3.7 Connections, pipes, hoses and fittings

The model elements are connected with connection elements. The type of hydraulic fluid in the system, whether to consider heat transfer and how to handle gas fraction in the oil can all be configure for the entire model in any of the connection elements property window. In our model we have the HLP46 hydraulic fluid, a constant oil temperature of 40°C and a gas fraction of 0.2% according to static pressure level as can be seen in Figure 24 (see also discussion chapter 6.3). In addition to these settings the initial pressure of every connection element can be set individually. In many cases this is indeed required in order to be able to run a simulation.



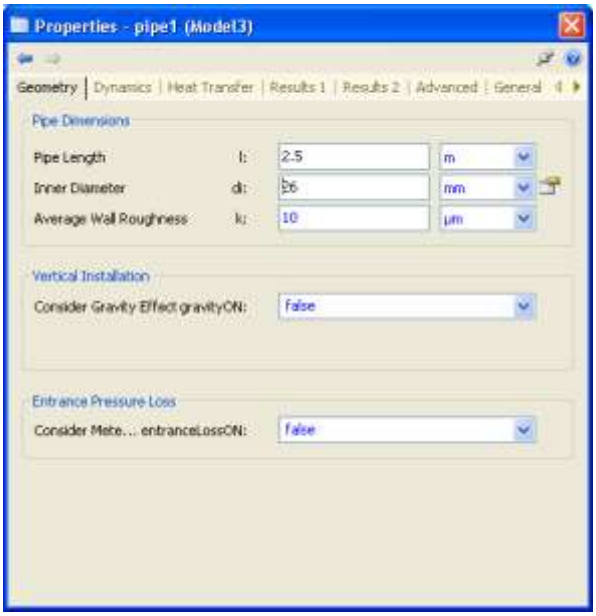
Hydraulic Fluid: HLP 46

Temperature Calculation:
● Constant Temperature
○ Consider Heat Transfer

Calculation of Gas Fraction:
● Gas fraction according to static pressure level
○ Consider dynamic absorption/dispersion of gas
○ Without Gas fraction

Initial Pressure (relative to pAtm) p0: p0_lftCylP Pa
Temperature Setting T1: 40 °C
Gas Fraction (Normal Sta...alphaURef: 0.2 %

Figure 24. The property window of the connection element type.



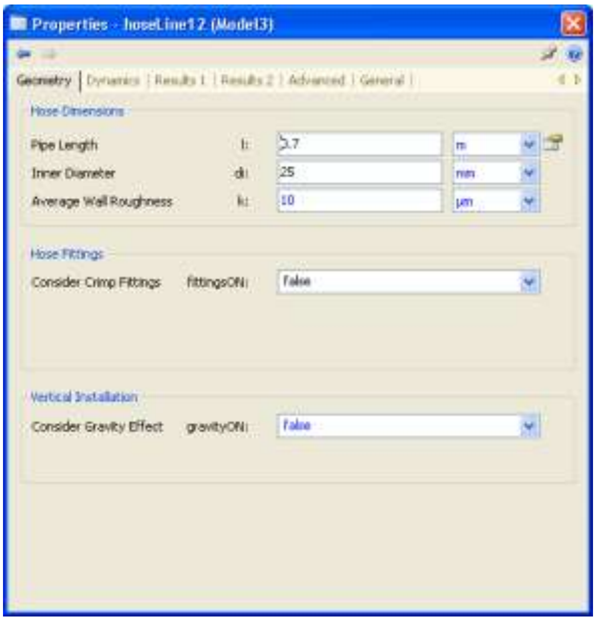
Pipe Length l: 2.5 m
Inner Diameter di: 26 mm
Average Wall Roughness k: 10 µm

Consider Gravity Effect gravityON: false

Consider Mete... entranceLossON: false

Figure 25. The property window of the pipe element type.

For the pipe elements, the pipe length and inner diameter is defined in the property window (see Figure 25). No gravity effects, entrance pressure losses, pipe dynamics or wall elasticity are considered for the pipe elements in order to simplify the model. The length and inner diameter of the hose elements are defined in a similar way as can be seen in Figure 26, and the hose elasticity is defined by default as can be seen in Figure 27. No hose fittings, gravity effects or dynamics are considered for the hose elements in order to simplify the model. No separate fitting are defined in the model. See also discussion about pipes, hoses and fittings in chapter 6.4.



Hose Dimensions

Pipe Length l: 3.7 m

Inner Diameter di: 25 mm

Average Wall Roughness k: 10 µm

Hose Fittings

Consider Crimp Fittings fittingsON: false

Vertical Installation

Consider Gravity Effect gravityON: false

Figure 26. The geometry tab of the hose element type.

Options

Consider Inertia of Flu... dynamicsON: false

Elastic Properties

Input Parameter elasticityKind: Volume Intake

Defined by valueKind: Value or Expression

Volume Intake dVdp: 0.03 cm³/m/bar

Initial Values

Figure 27. The dynamics tab of the hose element type.

3.4 Simulation run description

In order to demonstrate the hydraulic load handling system model a 90 seconds simulation run has been carried out. This was done by executing the *ETH1-02_Load sequence.vbs* VBScript found in Appendix 8. This script defines the diesel engine speed, container weight, M402 directional control valve spool positions, simulation stop time, initial cylinder pressures etcetera and then starts the simulation run automatically. The spool position input curves for the boom lift and extension functions can be seen in Figure 28 (see also discussion chapter 6.5).

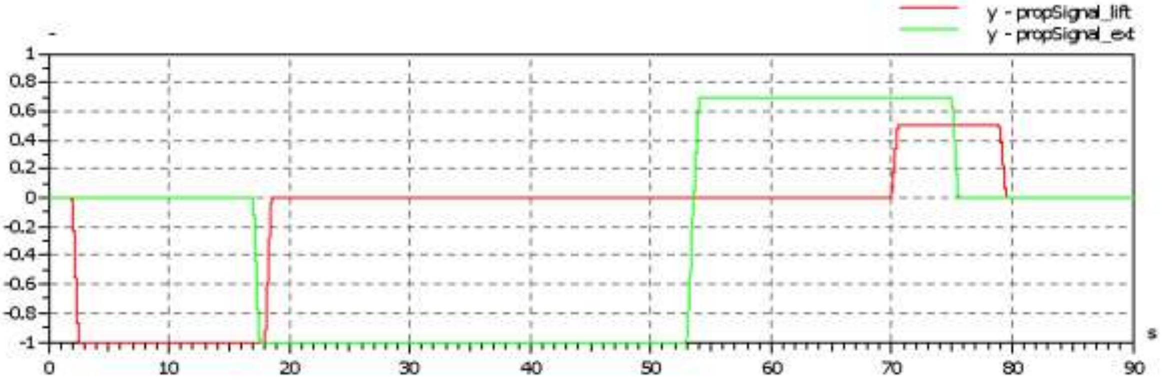


Figure 28. The spool position simulation input curves.

The simulation run (see 3D images in Appendix 2) begins by lifting a 30 ton container from transport position (approximately 34° boom angle) to maximum boom angle and then fully extending the boom. The boom is then fully retracted. Finally, the boom is lowered back to transport position. The boom angle and boom extension during the simulation run are visualized in Figure 29. See Appendix 1 for some variable definitions.

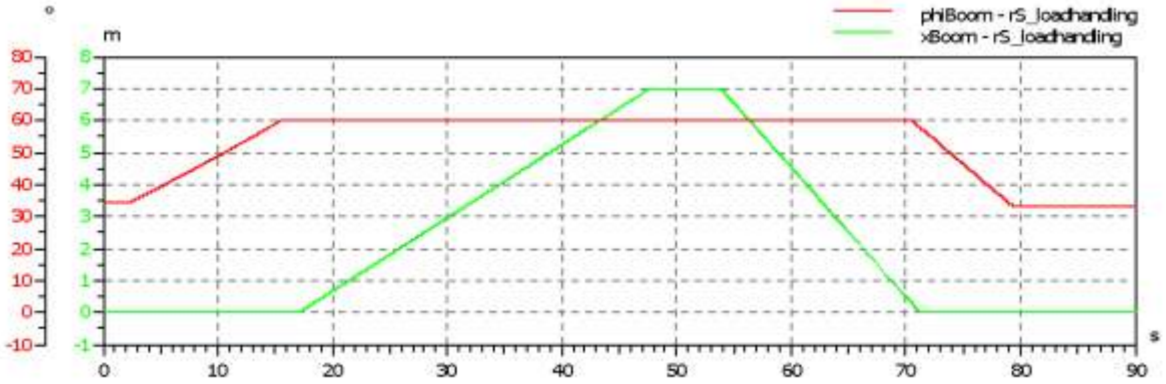


Figure 29. The boom angle, phiBoom, and boom extension, xBoom, during simulation run.

4 Results

4.1 Simulation run results

Complete simulation run calculation report created by the *ETH1-02_Load sequence.vbs* VBScript (see Appendix 9) can be seen in Appendix 10. Figure 30 shows the lift cylinder plus and minus pressures during the 90 seconds load sequence. During the initial lifting phase (2 < t < 16 s.) we can see that the plus pressure is starting at approximately 140 bars and declining to approximately 100 bars; and the minus pressure is remained quite constant at approximately 10 bars. This means declining cylinder forces at higher boom angles. The opposite behavior can be observed at the conclusive lowering phase at 70 < t < 80 seconds.

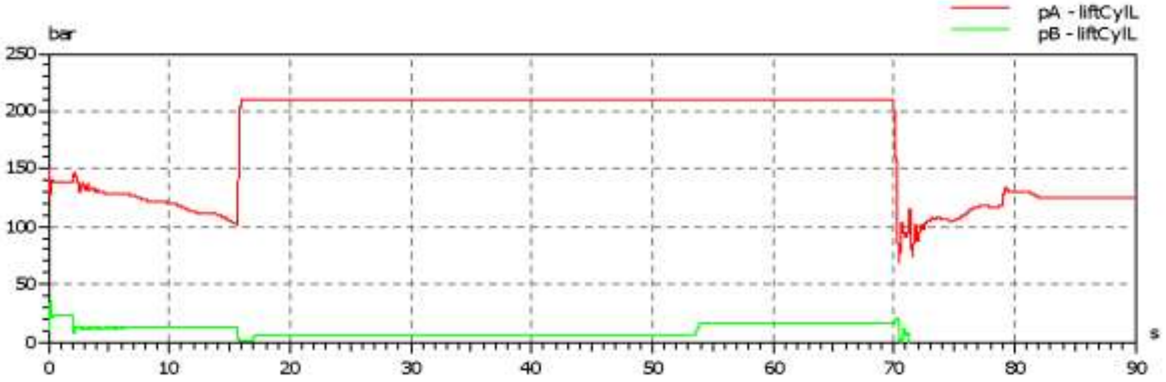


Figure 30. Lift cylinder pressures during 90 seconds load sequense.

Figure 31 shows the extension cylinder plus and minus pressures. In accordance to a constant load geometry both plus and minus pressures can be observed to be constant during both boom extension and retraction (extension at 17 < t < 48 and retraction at 53 < t < 72)

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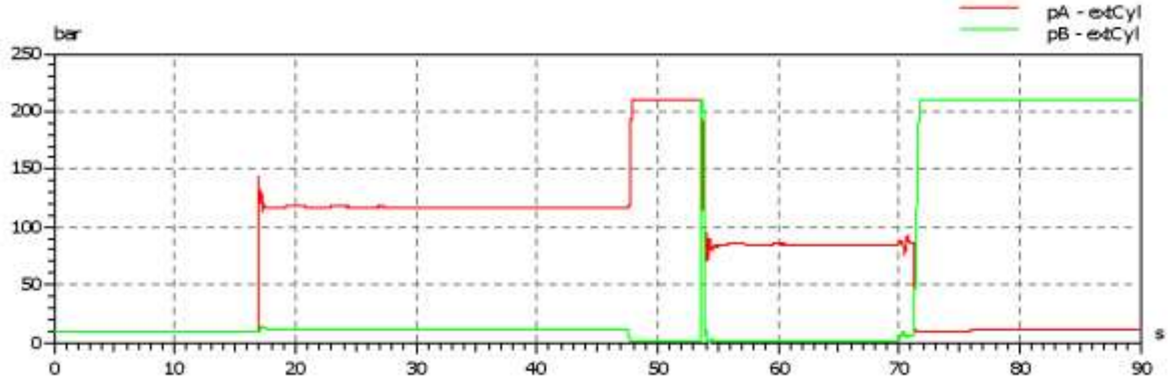

Figure 31. Extension cylinder pressures during 90 seconds load sequense.

5 Conclusions

The hydraulic reach stacker load handling system model described in this report is working fine for a number of different configurations of diesel engine speed, container weight and directional valve spool motions. A simulation run of a 90 seconds load sequence has been demonstrated in this report and all the result variables seen in chapter 4.1 and Appendix 10 seem reasonable. Since a hydraulic system model of this size easily can become very complex with plausible calculation problems and poor usability, our model has intentionally been kept as simple as possible. This is done for example by not considering dynamics for a number of components. The simplifications can probably be done with remained simulation accuracy for our purpose: energy system analysis. The model however needs to be verified by comparing simulation results to measurement data; and if the simulation accuracy then is shown to be inadequate the simplifications must be reevaluated.

6 Discussion

6.1 Pump efficiency

Correct data for calculating pump efficiency is important for the energy analysis but can be hard to find and also difficult to describe since both hydro-mechanical and volumetric losses are depending on pump speed, displacement and pressure. We have used a total pump efficiency map for a specific pump speed (see Figure 9) for defining the hydro-mechanical efficiency and then defined the volumetric losses as zero. This can result in acceptable energy analysis figures for some cases but would probably give incorrect figures for others, for example the pump idling losses since no leakages is considered. Hence defining hydro-mechanical and volumetric losses separately is recommended. The pump speed dependence of the efficiency should probably also be considered. There is a need for clarifying how the pump efficiency could be defined in an easy but yet accurate way.

6.2 Boom joint friction

No evaluation of the accuracy of the boom joint friction coefficients has been done. The boom rotational joint friction is probably rather small and rather constant, and a constant value would most likely lead to acceptable overall simulation accuracy. The same would probably yield for the spreader rotational joint when not damped. If the spreader rotational motion is damped by for example hydraulic damping cylinders, a more complex definition of the friction coefficient would be needed though. An even more complex definition of the friction would probably be needed for the boom extension joint because of the total friction force dependence on boom angle, boom extension and container weight. Some of the friction coefficients might have to be evaluated separately in order to get appropriate input data for the reach stacker MBS element type.

6.3 Oil properties

Oil properties and how to consider heat transfer and gas fraction in the oil can be configured in any of the connection elements. This might be of interest for the final adjustments of the model verification.

6.4 Pipes, hoses and fittings

Our model includes pipes and hoses but no fittings. The idea of this is that, for a system energy analysis, fittings could possibly be excluded with preserved model accuracy. This is however yet to be confirmed and the same yields to all the other hose and pipe characteristics being excluded.

6.5 Spool position input curves

As can be seen in Figure 24 the spool position input curves for the simulation run in this report is quite sharply defined. This is done for simplicity reasons but can lead to unnecessary heavy calculations at for example cylinder end stops. In real life the spool movements are much smoother and measurements on a reference system would help getting a better idea of how to best define the spool position curves.

7 References

[1] M. Hägglund, *MBS modeling of a reach stacker container truck using SimulationX software*, ITH technical report no. ETH1-01, Stiftelsen Institutet för Tillämpad Hydraulik (2011)

[2] www.cargotec.com, Image bank of Cargotec Corporation (2011-06-22)

[3] www.parker.com (2011-09-07)

Appendix 1

Definitions

Axle pressure (*ap*)

The axle pressure is defined as the total mass acting on one wheel axle. The sum of the two axle pressures (front and rear) equals the total mass of the vehicle including container weight as long as the container is not standing on the ground.

Boom angle (*phiBoom*)

The boom angle is defined as the angle between the boom and the horizontal plane of the vehicle (see *phiBoom* in Figure 1).

Boom extension (*xBoom*)

The boom extension is defined as the longitudinal displacement of the inner boom section in relation to the outer boom section (see *xBoom* in Figure 1). The value is zero when inner boom section is maximum withdrawn.

Effective rolling radius (*reTire*)

The effective rolling radius is defined as the tire radius that consists with the vehicle velocity and the angular velocity of the tire. The effective rolling radius varies with tire load.

Load center (*lcCont*)

The load center is defined as the horizontal distance between tire front edge and the longitudinal centre of the container (see *lcCont* in Figure 1).

Load height (*lhCont*)

The load height is defined as the vertical distance between the container bottom and ground (see *lhCont* in Figure 1)

Tire centre height (*tch*)

The tire centre height is defined as the vertical distance between the tire centre and the ground (see *tch* in Figure 1).

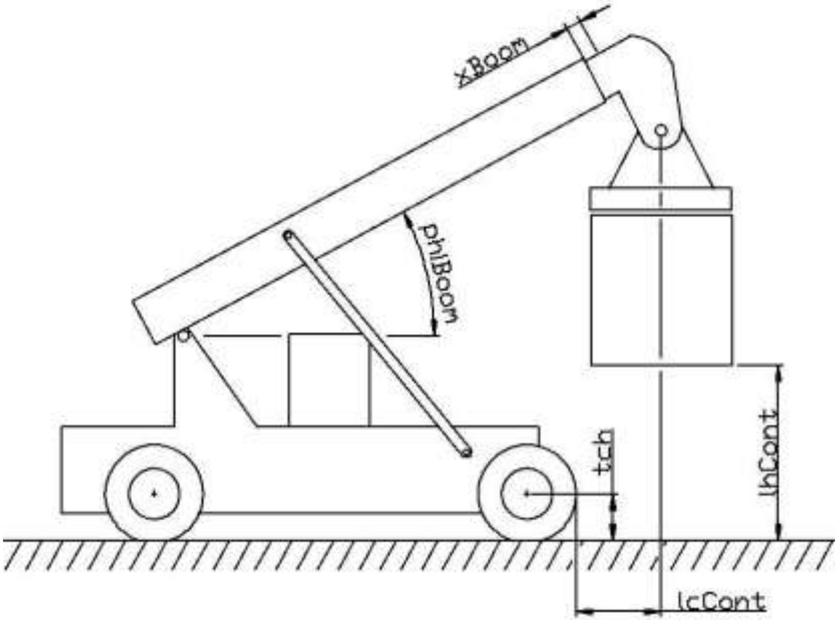

Figure 1. Some geometrical definitions.

Appendix 2

Images of the simulation run

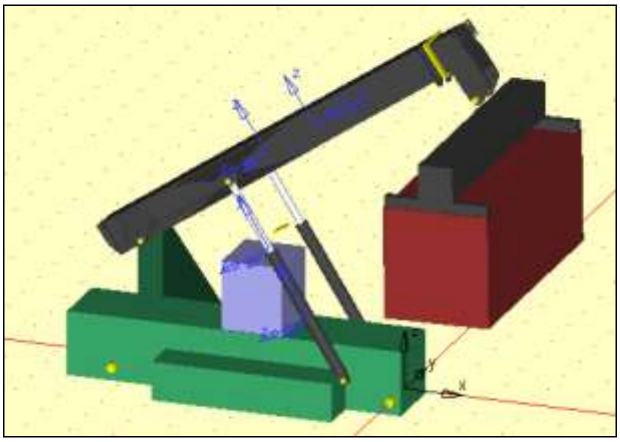

Figure 1. Starting lifting a 30 ton container from transport position (t=2 s.).

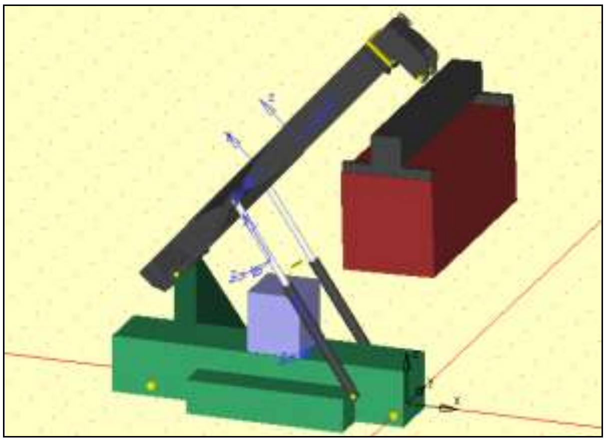

Figure 2. Lifting the container (t=10 s.).

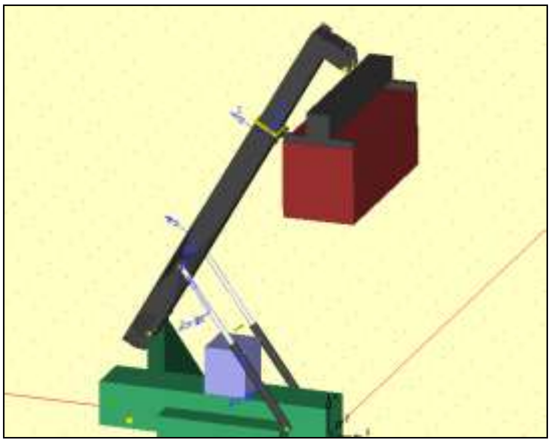

Figure 3. Extending the boom at maximum boom angle (t=30 s.).

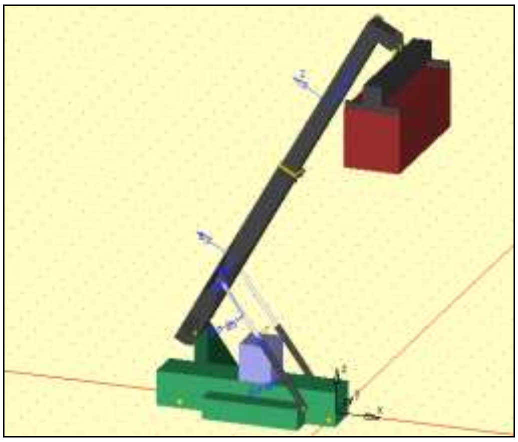

Figure 4. Resting at maximum boom angle and fully extended boom (t=50 s.).

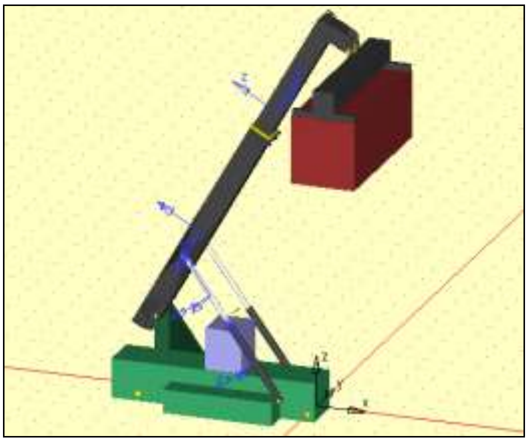

Figure 5. Retracting the boom (t= 60 s.).

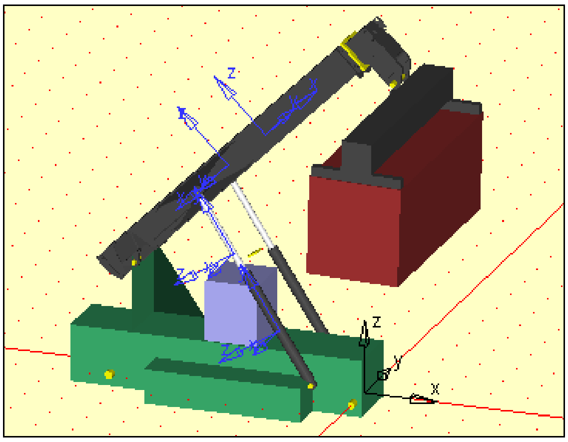

Figure 6. Lowering the container back to transport position (t=75 s.).