Institutet för Tillämpad Hydraulik

Technical Report

Document No.	ETH1-03
Title	Energy analysis of reach stacker load handling system using SimulationX software
Author	Magnus Hägglund
Date	2011-09-26

Energy analysis of a reach stacker load handling system using SimulationX software

Abstract

A number of load handling sequences have been simulated in SimulationX software using a conventional hydraulic reach stacker load handling simulation model and simulation results has been compared to measurement data. The objective of the simulation exercise was to evaluate the simulation model compliance with reality and to obtain a preliminary energy analysis of the system. The simulation results show a good overall compliance with reality but also identify a number of weak points of the model. Need for improvements mainly concern characteristics of valve components, boom friction forces and pump losses. A preliminary energy analysis has been carried out giving a rough picture of the real energy consumption and the real energy losses. The most important conclusions from the energy analysis are:

- For a lifting sequence, the hydraulic system overall energy efficiency is determined to 50-75 % depending on diesel engine speed and container weight.
- For a lifting sequence, full engine speed increases the total hydraulic energy input by up to 30 % compared to automatically controlled engine speed because of higher pressure drops in the system due to higher volume flows.
- For a lifting sequence, pumps and M402 directional control valve alone stands for over 50 % of total hydraulic system energy dissipation.
- For a lowering sequence, M402 directional control valve alone stands for over 50 % of total hydraulic system energy dissipation.

EUROPEISKA UNIONEN
Europeiska regionala utvecklingsfonden

Adress:	Tele-	Bankgiro	Postgiro	Org.nr	Vat.no
Stiftelsen Institutet för Tillämpad Hydraulik Sörbyvägen 1 SE-891 61 ÖRNSKÖLDSVIK ith@ith.se www.ith.se	fon: + 46 660 79850 fax: + 46 660 79859	920-6384	4800199-4	889600-8540	SE889600854001

Table of Contents

APPENDICES

1. 0 ton_lifting_auto.vbs – VBScript
2. ETH1-03_Lifting verification.vbs – VBScript
3. ETH1-03_Energy analysis_lifting.vbs – VBScript
4. ETH1-03-CR01 – Model verification: Lifting 0 ton (0.55 m, automatic)
5. ETH1-03-CR02 – Model verification: Lifting 0 ton (0 m, full)
6. ETH1-03-CR03 – Model verification: Boom out 0 ton (60°, automatic)
7. ETH1-03-CR04 – Model verification: Boom out 0 ton (60°, full)
8. ETH1-03-CR05 – Model verification: Boom in 0 ton (60°, automatic)
9. ETH1-03-CR06 – Model verification: Boom in 0 ton (60°, full)
10. ETH1-03-CR07 – Model verification: Lowering 0 ton (0 m, automatic)
11. ETH1-03-CR08 – Model verification: Lowering 0 ton (0 m, full)
12. ETH1-03-CR09 – Model verification: Lifting 27 ton (0 m, automatic)
13. ETH1-03-CR10 – Model verification: Lifting 27 ton (0 m, full)
14. ETH1-03-CR11 – Model verification: Boom out 27 ton (60°, automatic)
15. ETH1-03-CR12 – Model verification: Boom out 27 ton (60°, full)
16. ETH1-03-CR13 – Model verification: Boom in 27 ton (60°, automatic)
17. ETH1-03-CR14 – Model verification: Boom in 27 ton (60°, full)
18. ETH1-03-CR15 – Model verification: Lowering 27 ton (0 m, automatic)
19. ETH1-03-CR16 – Energy analysis: Lifting + boom out 0 ton (automatic)
20. ETH1-03-CR17 – Energy analysis: Lifting + boom out 0 ton (full)
21. ETH1-03-CR18 – Energy analysis: Lifting + boom out 27 ton (automatic)
22. ETH1-03-CR19 – Energy analysis: Lifting + boom out 27 ton (full)
23. ETH1-03-CR20 – Energy analysis: Boom in + lowering 0 ton (automatic)
24. ETH1-03-CR21 – Energy analysis: Boom in + lowering 0 ton (full)

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.

A 3D multi-body system (MBS) model [1] as well as a load handling hydraulic model [2] of a conventional reach stacker container truck has been built using the SimulationX software. Now simulation results based on these models have been compared to measurement data. Also an energy analysis has been done for some load handling sequences based on the simulation model in order to evaluate the energy losses of the system.

2 Objectives

The objective of the simulation exercise is to evaluate the simulation model compliance with reality. Also a preliminary energy analysis evaluating energy losses of the system is to be obtained for a number of load handling sequences by using the simulation model.

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). Verification measurements has been done on a Kalmar DRF450, machine number Z90213 [3].

Figure 1. Kalmar DRF450 reach stacker [4].

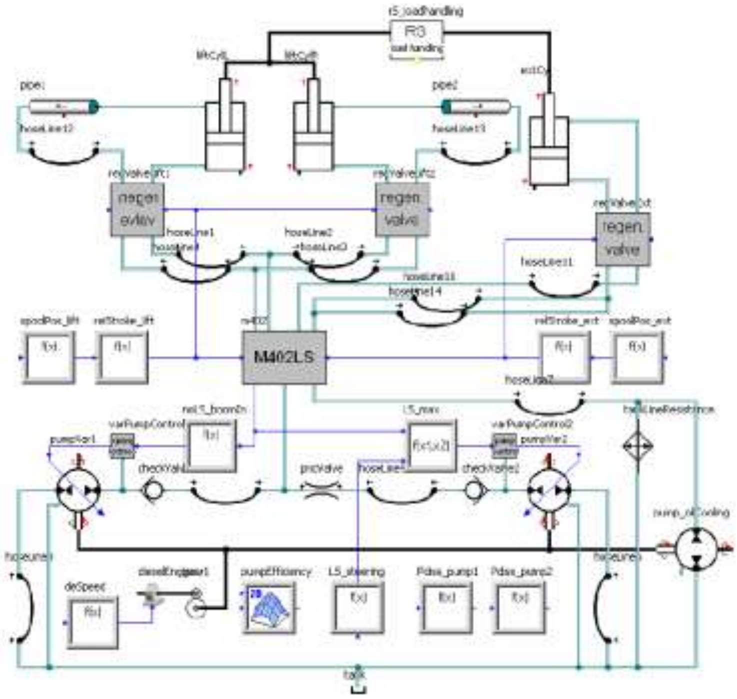

Figure 2. Hydraulic load handling simulation model.

3.3 Model description

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. The MBS model and the hydraulic model are further explained in [1] and

[2] respectively. A number of additional adjustments to the current simulation model have been made though. Main input parameters to the model are:

- Container weight [ton]
- Diesel engine speed [rpm]
- Directional control valve lift spool position [mm]
- Directional control valve extension spool position [mm]
- Regenerative lift signal [I/0]
- Regenerative extension signal [I/0]

3.4 Measurement description

Measurements have been carried out for lifting (0 m boom extension), boom out (60° boom angle), boom in (60° boom angle) and lowering (0 m boom extension). All sequences have been made with 0, 10, 27 and 45 ton container resulting in a total of 16 different load handling sequences. In addition these have all been carried out for fully actuating joystick at automatic engine speed, fully actuating joystick at full engine speed and for slowly increasing joystick actuation at full engine speed leading to a total of 48 measurements. Also, all 48 measurements were repeated with two flow turbines measuring both pump flows. More information about load handling sequences, measurement variables, gauge positions etcetera can be seen in [3].

3.5 Simulation run description

3.5.1 Model verification

In order to evaluate the simulation model the following 15 simulation runs at full joystick actuation have been carried out and compared to measured load handling sequences:

- Lifting, 0 ton @ automatic engine speed
- Lifting, 0 ton @ full engine speed
- Boom out, 0 ton @ automatic engine speed
- Boom out, 0 ton @ full engine speed
- Boom in, 0 ton @ automatic engine speed
- Boom in, 0 ton @ full engine speed
- Lowering, 0 ton @ automatic engine speed
- Lowering, 0 ton @ full engine speed
- Lifting, 27 ton @ automatic engine speed
- Lifting, 27 ton @ full engine speed
- Boom out, 27 ton @ automatic engine speed
- Boom out, 27 ton @ full engine speed
- Boom in, 27 ton @ automatic engine speed
- Boom in, 27 ton @ full engine speed
- Lowering, 27 ton @ automatic engine speed

The simulation runs were carried out by executing a VBScript specially designed for the current load handling sequence (see example in Appendix 1: *0 ton_lifting_auto.vbs*). This script defines the container weight, simulation start and stop time, initial cylinder pressures etcetera. It also imports measured diesel engine speed, M402 directional control valve spool positions and regenerative signals; and defines this data to corresponding input parameters.

3.5.2 Energy analysis

In order to analyze the system energy consumption for a number of load handling sequences the following 6 simulation runs at full joystick actuation have been carried out:

- Lifting + boom out, 0 ton @ automatic engine speed
- Lifting + boom out, 0 ton @ full engine speed
- Lifting + boom out, 27 ton @ automatic engine speed
- Lifting + boom out, 27 ton @ full engine speed
- Boom in + lowering, 0 ton @ automatic engine speed
- Boom in + lowering, 0 ton @ full engine speed

The simulation runs were based on the same input parameters from measurements as being used in verification simulation runs described in chapter 3.5.1.

3.6 Energy analysis method

Energy consumption and losses have been calculated in the SimulationX simulation software for selected load handling sequence. In the energy analysis calculation reports, first all hydraulic system power inputs and outputs of the simulation run are shown in graph 6. The areas under the graphs are then calculated and presented in table 2 as the energy inputs and outputs. Graph 7 then shows all power dissipation of the hydraulic system and corresponding energy dissipations are presented in table 3. A similar analysis is done for the boom mechanical system where graph 8 shows power inputs and outputs and table 4 shows corresponding energy inputs and outputs. Graph 9 shows power dissipation of the boom mechanical system and table 5 shows corresponding energy dissipation. There are two graphs in the end of the report showing pump operating conditions during the simulation run. Finally the total energy inputs and energy outputs are compiled and presented together with system efficiencies in table 1.

For lifting sequences table 1 shows *pump work* as the only energy input post and *cylinder work* as well as *useful container work* as energy output posts. *Useful container work* here refers to the gain in potential energy of the container. The first energy efficiency figure should be interpreted as a hydraulic overall system efficiency, the second energy efficiency figure as a boom mechanical overall system efficiency and the third energy efficiency figure as the total overall system efficiency based on the energy input of the hydraulic pumps.

For lowering sequences table 1 shows both *pump work* and *cylinder work* as energy input posts and *accumulated in energy storage* as energy output post. Our system however doesn't have any energy storage and thus the energy output post as well as the system efficiency remains zero for all simulation runs being analyzed.

4 Results

4.1 Model verification

Model verification calculation reports for load handling sequences specified in chapter 3.5.1 were generated by executing a VBScript (see example in Appendix 2: *ETH1-03_Lifting verification.vbs*) and can be seen in Appendix 4-18. The graphs of the verification reports are commented below.

4.1.1 Graph 1-2: Measurement data

The first two graphs show measured system pressures during the load handling sequence.

4.1.2 Graph 3-7: Input parameters

The following five graphs show measured diesel engine speed, M402 directional control valve lift and extension spool positions as well as lift and extension regenerative signals. These measured data are also given as input parameters to the simulation run.

4.1.3 Graph 8-10: Boom motion

The following three graphs show simulated and measured boom motion in the figures of boom angle, boom extension and load centre distance from front tire centre respectively. For lifting and boom out motions the boom velocity depends on the diesel engine speed and the variable pumps maximum displacement only since the LS pump control never reach desired differential pressure. This means that simulation and measurement results have a very good compliance for lifting and boom out simulation runs. For boom in and lowering motions however, the boom velocity strongly depends on the tank counter pressure. Here the M402 directional control valve spool characteristics have been adjusted in order to get a decent compliance for simulation and measurement results.

4.1.4 Graph 11-15: Pump pressures

Graph 11, 12 and 13 show the pump pressure at M402, pump 1 and pump 2 respectively and graph 14 and 15 shows the pump line differential pressure for pump 1 and pump 2 respectively. The simulated pump line differential pressure is important for the LS pump control to be working correctly. Therefore the pressure drop of the components between pumps and M402 has been adjusted in order to get simulated results to comply measurement results. Pump pressure and pump line differential pressure simulation results show good compliance with measurement data with some exceptions:

- Boom out with 27 ton container shows approximately 15 bar lower pump pressures in reality compared to simulation results
- Pump pressure at boom in without container
- Pump line differential pressures at boom in with 27 ton container indicating incorrect pump flows
- Pump pressure and pump line differential pressure, pump 1, at lowering indicating a small pump flow in reality and caused by a small LS pressure

4.1.5 Graph 16-20: LS pressures

Graph 16, 17 and 18 show the LS pressure at M402, pump 1 and pump 2 respectively and graph 19 and 20 shows the pump control differential pressure, deltaP, for pump 1 and pump 2 respectively. The pump control differential pressure is the sum of the pump line differential pressure shown in graph 14 and 15, and the pressure drop over the M402 valve. The simulated LS pressures show similar compliance with measurement data as the pump pressures discussed in chapter 4.1.4. The compliance is somewhat worse though caused by incorrect defined M402 spool characteristics (see also chapter 4.1.7).

4.1.6 Graph 21-25: Cylinder pressures and M402 tank counter pressure

Graph 21, 22, 23 and 24 show the cylinder pressures at both regenerative valve and M402 valve for lift or extension cylinder depending on current load handling sequence. Graph 25 always shows the tank counter pressure at M402 directional control valve.
The cylinder pressures during boom motions have been briefly studied and the boom extension friction coefficient slightly adjusted in order to receive fairly correct cylinder pressures. This needs to be looked into even more though. Especially cylinder pressures at boom out and boom in with 27 ton container which have a bad compliance with measurement data. The tank counter pressure at M402 directional control valve depends not only on the load handling functions but also on the oil cooling system since both systems share the same tank line. Therefore the simulation model of [2] has been expanded with a constant displacement oil cooling pump and a tank line resistance component adapted in order to give a fairly correct simulated tank counter pressure at M402.

4.1.7 Graph 26-30: M402 and regenerative valve differential pressures

Graph 26 and 27 show the M402 spool differential pressures depending on current load handling sequence. An inadequate compliance with measurement data here indicates poorly defined spool characteristics. Graph 28, 29 and 30 show the regenerative lifting/extension valve differential pressure over load handling valve, regenerative valve and check valve respectively. Many of these show a better compliance with measurement data at higher flow rates (full engine speed). Overall, similar to the M402 spool characteristics, an inadequate compliance with measurement data indicates poorly defined regenerative valve components characteristics.

4.1.8 Graph 31-34: Cylinder and pump volume flow

Graph 31, 32, 33 and 34 show the pump 1 volume flow, pump 2 volume flow, lift/extension cylinder (+) and lift/extension cylinder (-) volume flow respectively. These graphs show simulation results only since no measurement data was available for selected load handling sequences. Additional measurements with two flow turbines measuring pump flows are available for further analysis though.

4.2 Energy analysis

Energy analysis calculation reports for load handling sequences specified in chapter 3.5.2 were generated by executing a VBScript (see example in Appendix 3: *ETH1-03_Energy analysis_lifting.vbs*) and can be seen in Appendix 19-24. See chapter 3.6 for more information about the method used for the energy analysis.

4.2.1 Lifting without load

Fully lifting followed by fully extending the boom has been simulated without load and with both automatically controlled and full diesel engine speed (~800 rpm and ~2000 rpm respectively). Calculation reports can be seen in Appendix 19 and 20; and results in brief can be seen in Table 1 and Table 2 respectively.

Table 1. Lifting 0 ton with automatically controlled diesel engine speed (~800 rpm) gives a hydraulic energy efficiency of approximately 68 %.

Comment	Energy [kJ]	System efficiency
Energy input		
- Pump work (pump 1+2)	3297	
Energy output		
- Cylinder work (lift + extension)	2249	68,2 %
- Useful container work (potential energy)	0	0 %
		---------
		0 %

Table 2. Lifting 0 ton with full diesel engine speed (~2000 rpm) gives a hydraulic energy efficiency of approximately 53 %.

Comment	Energy [kJ]	System efficiency
Energy input		
- Pump work (pump 1+2)	4282	
Energy output		
- Cylinder work (lift + extension)	2277	53,2 %
- Useful container work (potential energy)	0	0 %
		---------
		0 %

In the figures we can see that lifting with full diesel engine speed results in an approximately 30 % higher hydraulic system energy input compared to automatically controlled engine speed. This is probably caused by higher pressure drops in the system due to higher volume flows. This is also reflected in the considerably higher hydraulic system energy efficiency of 68 % at 800 rpm diesel engine speed compared to 53 % at 2000 rpm engine speed. We can also see that the total cylinder work of the two simulation runs marginally differs though it likely should be exactly the same whether lifting at 800 or 2000 rpm engine speed. This is explained by differing initial boom extension displacement (0 meter versus 0.55 meter) for the measurement data used for simulation input parameters. Since the lifting sequence is carried out without load we don’t have any useful container work.

Table 3 and Table 4 show the energy dissipation of each hydraulic component for automatically controlled and full diesel engine speed respectively. We can see that pumps and M402 directional control valve alone stands for over 50 % of total energy dissipation. We can also see that the increasing energy dissipation when lifting at full diesel engine speed is mainly caused by resistance components like valves where an increased volume flow leads to higher pressure drops.

Table 3. Energy dissipation of each hydraulic component when lifting 0 ton with automatically controlled diesel engine speed (~800 rpm).

Table 4. Energy dissipation of each hydraulic component when lifting 0 ton with full diesel engine speed (~2000 rpm).

Comment	Energy [kJ]
Pump 1	Company internal information
Pump 2	
Cylinder friction (lift + extension)	
Directional valve, M402	
Regeneration valve 1, lift	
Regeneration valve 2, lift	
Regeneration valve, extension	
Hoses	
Check valves	
Steering priority valve	
Tank line resistance	
Total	

4.2.2 Lifting 27 ton container

Fully lifting followed by fully extending the boom has been simulated with 27 ton container and with both automatically controlled and full diesel engine speed (~1000 rpm and ~2000 rpm respectively). Calculation reports can be seen in Appendix 21 and 22; and results in brief can be seen in Table 5 and Table 6 respectively. In the figures we can see that lifting with full diesel engine speed results in an approximately 10 % higher hydraulic system energy input compared to automatically controlled engine speed. This is probably caused by higher pressure drops in the system due to higher volume flows. This is also reflected in the somewhat higher hydraulic system energy efficiency of 77 % at 1000 rpm diesel engine speed compared to 69 % at 2000 rpm engine speed. We can also see that both the total cylinder work and the useful container work of the two simulation runs are almost identical leading to a boom mechanical overall system efficiency of approximately 55 %.

Table 5. Lifting 27 ton with automatically controlled diesel engine speed (~1000 rpm) gives a hydraulic energy efficiency of approximately 77 %.

Comment	Energy [kJ]	System efficiency
Energy input		
- Pump work (pump 1+2)	8042	
Energy output		
- Cylinder work (lift + extension)	6161	76,6 %
- Useful container work (potential energy)	3399	55,2 %

		42,3 %

Table 6. Lifting 27 ton with full diesel engine speed (~2000 rpm) gives a hydraulic energy efficiency of approximately 69 %.

Comment	Energy [kJ]	System efficiency
Energy input		
- Pump work (pump 1+2)	8871	
Energy output		
- Cylinder work (lift + extension)	6112	68,9 %
- Useful container work (potential energy)	3360	55 %

		37,9 %

Table 7 and Table 8 show the energy dissipation of each hydraulic component for automatically controlled and full diesel engine speed respectively. Similar to the results for lifting without load (see chapter 4.2.1) we can see that pumps and M402 directional control valve alone stands for over 50 % of total energy dissipation. Also, the increasing energy dissipation when lifting at full diesel engine speed is mainly caused by resistance components like valves where an increased volume flow leads to higher pressure drops.

Table 7. Energy dissipation of each hydraulic component when lifting 27 ton with automatically controlled diesel engine speed (~1000 rpm).

Comment	Energy [kJ]
Pump 1	Company internal information
Pump 2	
Cylinder friction (lift + extension)	
Directional valve, M402	
Regeneration valve 1, lift	
Regeneration valve 2, lift	
Regeneration valve, extension	
Hoses	
Check valves	
Steering priority valve	
Tank line resistance	
Total	

Table 8. Energy dissipation of each hydraulic component when lifting 27 ton with full diesel engine speed (~2000 rpm).

Comment	Energy [kJ]
Pump 1	
Pump 2	
Cylinder friction (lift + extension)	
Directional valve, M402	
Regeneration valve 1, lift	
Regeneration valve 2, lift	
Regeneration valve, extension	
Hoses	
Check valves	
Steering priority valve	
Tank line resistance	
Total	

Company internal information

4.2.3 Lowering without load

Fully retracting the boom followed by fully lowering has been simulated without load and with both automatically controlled and full diesel engine speed (~700 rpm and ~2000 rpm respectively). Calculation reports can be seen in Appendix 23 and 24; and results in brief can be seen in Table 9 and Table 10 respectively. In the figures we can see that lowering with full diesel engine speed results in approximately 200 % higher pump energy input compared to automatically controlled engine speed. There is however rather high uncertainties in these figures since there are some inadequate definition of the pump characteristics and especially the volumetric losses (see also chapter 6.1).

Table 9. Lowering 0 ton with automatically controlled diesel engine speed.

Comment	Energy [kJ]	System efficiency
Energy input		
- Pump work (pump 1+2)	441	
- Cylinder work (lift + extension)	1647	
Energy output		
- Accumulated in energy storage	0	0 %
		----------
		0 %

Table 10. Lowering 0 ton with full diesel engine speed.

Comment	Energy [kJ]	System efficiency
Energy input		
- Pump work (pump 1+2)	1325	
- Cylinder work (lift + extension)	1627	
Energy output		
- Accumulated in energy storage	0	0 %
		----------
		0 %

Table 11 and Table 12 show the energy dissipation of each hydraulic component for automatically controlled and full diesel engine speed respectively. We can see that M402 directional control valve alone stands for approximately 50 % of total energy dissipation. We can also see that the increasing energy dissipation when lifting at full diesel engine speed is rather evenly distributed over the components.

Table 11. Energy dissipation of each hydraulic component when lowering 0 ton with automatically controlled diesel engine speed (~700 rpm).

Comment	Energy [kJ]
Pump 1	Company internal information
Pump 2	
Cylinder friction (lift + extension)	
Directional valve, M402	
Regeneration valve 1, lift	
Regeneration valve 2, lift	
Regeneration valve, extension	
Hoses	
Check valves	
Steering priority valve	
Tank line resistance	
Total	

Table 12. Energy dissipation of each hydraulic component when lowering 0 ton with full diesel engine speed (~2000 rpm).

Comment	Energy [kJ]
Pump 1	Company internal information
Pump 2	
Cylinder friction (lift + extension)	
Directional valve, M402	
Regeneration valve 1, lift	
Regeneration valve 2, lift	
Regeneration valve, extension	
Hoses	
Check valves	
Steering priority valve	
Tank line resistance	
Total	

5 Conclusions

5.1 Model verification

The reach stacker load handling system simulation model's compliance with reality has been evaluated by comparing simulation results with measurement data for 15 different load handling sequences. The evaluation shows a good overall compliance but also identifies a number of weak points of the model. This is probably mainly caused by inadequate definitions of component characteristics. It would probably be a good idea to improve the characteristics definitions of components such as the M402 directional control valve and regenerative valves in order to improve the simulation model. Another weak point is the boom friction forces, especially in the boom extension joint. These forces haven't been determined in reality and a better definition of these in the model would be desirable.

5.2 Energy analysis

As been discussed in chapter 4.1 and chapter 5.1 the simulation model has a number of weak points. This however doesn't mean that it can't be used for analyzing energy consumption. The results of the energy analysis is not absolutely correct but should be considered to give a rough picture of the real energy consumption and the real energy losses. The most important conclusions from the energy analysis are:

- For a lifting sequence, the hydraulic system overall energy efficiency is determined to 50-75 % depending on diesel engine speed and container weight.
- For a lifting sequence, full engine speed increases the total hydraulic energy input by up to 30 % compared to automatically controlled engine speed because of higher pressure drops in the system due to higher volume flows.
- For a lifting sequence, pumps and M402 directional control valve alone stands for over 50 % of total hydraulic system energy dissipation.
- For a lowering sequence, M402 directional control valve alone stands for over 50 % of total hydraulic system energy dissipation.

6 Discussion

6.1 Simulation model improvements

Even if the evaluation of the simulation model compliance with reality shows promising results there is still a need for improvements. As can be read in chapter 4.1.7 the simulated differential pressures of M402 directional control valve spools as well as regenerative valve components was considered to have an inadequate compliance with measurement data. This indicates poorly defined component characteristics and will probably be the most significant step in improving the accuracy of the model. In addition to this there are also needs of improved definitions of for example pump losses and boom joint friction as been previously discussed in [2].

6.2 Measurements not yet being analyzed

A rather comprehensive evaluation of the simulation model compliance with reality has been done by analyzing the 15 simulation runs specified in chapter 3.5. This comprises load handling sequences without load as well as with 27 ton container. In addition to these there exist measurement data with 10 and 45 ton container not being analyzed. Also, all measurements were repeated with two flow turbines measuring the main pump flows which could be helpful in order to verify pump flows in the simulation model. However, for these measurements consideration has to be taken for the pressure drop of the flow turbines (see Figure 3). This is affecting the LS pump control which may lead to incorrect lift and extension velocities when pumps are not at fully displacement.

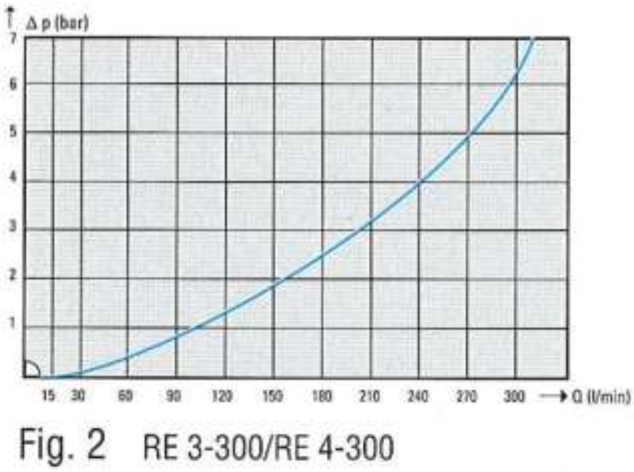

Figure 3. Typical flow turbine pressure drop at 30 cSt [5].

Additional measurements not being analyzed is all the load handling sequences carried out by slowly increasing the joystick actuation. These could for example be used for examining the M402 direction control valve spool characteristics more in detail. Energy analysis of additional load handling alternatives would probably be the most interesting use in general of the measurements not yet being analyzed though.

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] M. Hägglund, *Hydraulic modeling of a reach stacker container truck using SimulationX software*, ITH technical report no. ETH1-02, Stiftelsen Institutet för Tillämpad Hydraulik (2011)

[3] T. Karlsson, *Energy analysis measurement*, Kalmar technical report no. TR011307, Cargotec Sweden AB (2011)

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

[5] *Measuring turbines for flow-rate: RE3 and RE4*, Hydrotechnik data sheet no. 8898-01-00.21, Hydrotechnik GmbH (12/97)