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Aalesund University College

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SimulationX-based Simulation of Offshore Hydraulic Crane Systems with Active Heave Compensation and Anti-sway Control

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PREFACE

This master thesis project is mainly for accomplishment of the my study at Aalesund University College (MSc. Product and system design). Also as a conclusion of my 2 years study life in Norway.

I started the thesis work from January 2014 to May 2014, including the report writing. I have faced a lot of problems and challenges during the past 5 months. Through working on this master thesis I have also learned a lot. Thanks for my supervisors, Professor HouXiang zhang, Vilmar Æsøy. You have given me very inspiring and helpful instructions not only on the project work but also the thesis roport writing and study method.

Thanks for problems solving help from Yinguang Chu. You give me great support in using simulaitonX. And the previous work you have done also help me a lot.

Thank my family and all my friends always believe and support me.

Without all of your help I would not have gone so far in such an intense period. Because of the limitation of my knowledge.

There are still a lot of works need to continue after my work in this area. I hope my wrok can help the continue research work in the future.

Best.

Aalesund University College

May. 2014

Yao Cheng

CONTENTS

TERMINOLOGY

Symbols

Q flow [l/min]

P pressure [bar]

∀ displacement [l/rev]

F force[N]

T torque [Nm]

${}^{i+1}_{i}T$ transformation matrix

${}^{i+1}_{i}R$ rotation matrix

${}^{i}J$ Jacobian matrix

${}^{i}V$ velocity vector

${}^{i}\dot{\theta}$ angular velocity vector

θ_i angle

α_{i-1} angle

a_{i-1} distance

d_i distance

L_i link length

a acceleration

v velocity

B_{eq} equivalent bulk modulus

B_T constant temperature bulk modulus

t pipe wall thickness

E Young’s modulus

n gear ratio

Abbreviations

BIP Business Innovation Program

PHC Passive Heave Compensation

AHC Active Heave Compensation

3DM 3D Mechanics Editor

JLOTS Joint Logistics Over The Shore Operations

D-H Denavit-Hartenberg

DOF(s) Degree Of Freedom(s)

UG NX an advanced high-end CAD/CAM/CAE software package developed by Siemens PLM Software

ABSTRACT

In this master thesis project, an offshore hydraulic crane was been modeled and simulated. 3D model of the crane was made in siemens NX8.5 then converted to simulationX. Hydraulic system includ active heaven compensation and anti-sway also were designed based on simulationX. Through the simulation of the model, one can study the performance of the hydraulic systems during crane operations. AHC algorithm was developed based on kinematics solving method. Anti-sway control algorithm was proposed based on energy dissipating method.

KEYWORDS:

Offshore crane , 3D modelling , simulation , hydraulic , simulationX , 20sim , active heave compensation ， anti-sway.

1 INTRODUCTION

Nowadays the offshore operation is becoming more and more frequently and important. Facing to the winds, sea waves and other harsh environments, earlier offshore operations should waiting for the acceptable weather condition to reduce the risk. A great deal of time was lost and many accidents were happened because of this.

Because the offshore cranes are the major manipulating actors equipped on vessels and platforms for handling and transferring objects. So it should adapt all kinds of harsh environment conditions during the offshore operations. This is the main challenge of the offshore crane operation control.

Another challenge comes from the crane itself. When we design an offshore crane we need consider not only the working capacity of it but also the kinematic models of their own structure as well as an even more complex model of the environment. So the control of offshore crane is always a challenging task since it involves many problems such as load sway, ship motion, etc.

Most of the offshore cranes are hydraulic actuated cranes. As we know, the hydraulic system is widely used in industry areas. However this kind of driving mechanism also has its own week points.

The advantages of hydraulic system allow actuation of large control surfaces with minimal input, which is much more effective than electrical systems at high load items.

The disadvantages of the hydraulic system are poor efficiency, oil leakage and spill, system cooling problems, complicate in design and maintenance. Bring up high-level requirements to the hydraulic system design and application.

The subsea operation like landing the payload on the seabed requires a stable weather condition, because the ship motion generated by the wave makes undesirable impacts on the payload directly. An active heave compensated crane could compensate the heave motion of the vessel to minimize the impact of payload.

The purpose of AHC is to keep a load, held by equipment on a moving vessel. Commercial offshore cranes usually use some methods of motion detection to measure the current ship movement.

In this project, an active compensated winch crane is designed and simulated based on the utilizations of UGNX8.5[1] and simulationX[2].

1.1 Scope of work

3D modelling part

- Modeling and simplify the crane 3D model in NX8.5
- Some FEM analysis and modify of the crane model
- Convert the simplified 3D model to SimulationX for dynamic control

Develop a SimulationX model for crane control

- Hydraulic control system design
- Create models for the main hydraulic components
- Slew ring hydraulic system modeling and simulation
- Main derrick hydraulic system modeling and simulation
- Elbow derrick cylinder hydraulic modelling and simulation
- Simulation of active heaven compensation
- Simulation of anti-sway control of the crane
- Perform simulation and discuss results

Result compare and conclusions

- Different working conditions are introduced and compared
- Conclusions

1.2 Project contributions and benefits

To provide a 3D modelling for offshore crane simulaiton and dynamic control.

To develop an active heaven compensation for offshore crane.

To develop an anti-sway control model for offshore crane .

To combine knowledge of complementary disciplines: mechanics, hydraulics, and maritime industry.

To compare and evaluate two simualtion software 20-sim and simulationX

1.3 Report structure

I divided the text of the report into four chapters.

Part one is chapter 1 and 2. This part is the introduce part. All the basic methods and the main working aims will be explained in this part.

Part two is the chapter 3. This part is the modelling part. In chapter 3.2 and 3.3 we introduce the 3D mechanical model of crane. The rest part is the hydraulic system in the offshore crane, include the slew tower system, two cylinder control systems and the winch control system.

Part three are all the rest chapters. In chapter 4 and 5 we investigated and simulated crane control applications AHC control and anti-sway control system. Chapter 6 and 7 are the disscussion and conlcusion parts. These parts i evaluate the work i have finished and discuss the mistakes i have made. The chapter 8 i talk the further work about this thesis project and give some advices about the use of simulationX.

2 BACKGROUND AND THEORETICAL BASIS

2.1 Background

Offshore operation is related on many areas.

Fishery is a traditional way to get food. Nowadays fishery is a vital and indispensable part to the national economy and living of people especially in some country which has long coast line. In Norway the fishery is one of the biggest economic incomes. Statics from the fishery and aquaculture organization of the United Nations shows that in 2010 fishery and aquaculture capture provided 148 million tons fish to the world, of which 128 million tons were utilized as food.[3]

Human began to mine the ocean floor for diamonds, gold, silver, metal ores like manganese nodules and gravel mines in the 1950s when the company Tidal Diamonds was established by Sam Collins. Diamonds are found in greater number and quality in the ocean than on land, but are much harder to mine. When diamonds are mined, the ocean floor is dredged to bring it up to the boat and sift through the sediment for valuable gems. The process is different as sediment is not easy to bring up to the surface, but will probably become a huge industry once technology evolves to solve the logistical problem.[4]

Because of the limitation of natural resource, people start to consider changing or reducing the use of petroleum. With the Carbon emissions and environment pollution people need new clean and renewable natural gas and oil which in the ocean is enormous. This forces people to explore the ocean and the offshore operations become more and more famous and widely used.

In maritime applications, offshore cranes are widely used for hoisting objects and transporting goods. Because of this, offshore constructions and subsea operations are calling for more advanced technology and tools. Along with the development of technology, human activities could extend further and further from the coastlines to the center of the ocean.[5]

Crane operations are very complex projects. Consider to the safety and reliable control, crane structure, current crane operation is through joint-by-joint control and depends on the operator's working experiences and skills. We can find the main problems of this. Because of the weather conditions, the wind and wave will affect the crane operation and cause some accidents. A great deal of time and cost would be wasted on just waiting for better weather conditions that suitable for work. Except the weather problems the crane operations are also effected by the control systems, hydraulic system failures, human errors, all these potential risks may lead to a huge increase of coast and unexpected loss.

2.2 Research method and tools

To test the crane control system including the proposed theories and methods for AHC, firstly we model and simulate the crane and the hydraulic system of it in virtual environment. Through the modelling we can get a typical and simplified system. Even a thorough understanding of the system and detailed performance of the system's operation over a certain time period. Modelling and simulation can be used for testing the hypotheses of the system like weather the AHC theory can solve the ship motion problems and even help to discover the weak points of potential effects and failures. It helps to reduce the design and develop time and make the system reliable.

Consider to the offshore crane system, the operation capability and work performance of the crane are the key emphasis for my study. The main aim is to avoid the accident and failures of system. So we need to model the crane system and simulate the system operation in adverse working conditions in order to develop corresponding control programs. We should combine the 3D modelling of the crane and the hydraulic system together to investigate the possibility of improving the crane operation ability and accuracy.

2.3 Modelling and simulation

Through the modelling and simulation of the crane system. We can understand the system and detailed performance of the system's operation over a certain time period. As the pervious introduce of the modelling and simulation we can know that these two methods can be used for testing and finding the potential problems before the real crane been produced. By modelling and simulation it helps to reduce the design and develop time, cost, and foremost help to improve and optimize the system.

The modelling tool I used in my thesis is Siemens NX8.5. The NX formerly known as NX Unigraphics or usually just UG is an advanced high-end CAD/CAM/CAE software package developed by Siemens PLM software. It is wildly used by engineers and designers for modelling, analysis or doing the structure analysis. The modelling of the software can built in each detail part and been assembled together. NX8.5 is a well-developed 3D modelling tool which also supports many general formats. Like STL files can be imported into 20sim animation window. NX solutions for simulation include NX CAE, which is a modern, multi-discipline CAE environment for advanced analysis. Workgroups and designers who need to deliver high quality performance insights in a timely fashion to drive product decisions. NX CAE integrates best in class analysis modelling with simulation solutions for structural, thermal, flow, motion, engineering optimization, metaphysics, and simulation data management, and simulation driven design into a single environment.

2.4 Active heaven compensation

To solve the vessel motion problems during the offshore operation. The heaven compensation is the best way in this area. The concept is to control the crane by solving its kinematics model. The model will give the flexibility for different types of crane control and compensate the heaven motion through the crane itself instead of altering the wire length through the winch system. The crane is controlled through solving the relation between the crane tip velocities and the crane joints angular velocities. The heave compensation is to give the opposite signals to the crane control system, and then the system will use the kinematic matrix to calculate the crane tip position and keep the crane tip stable.
Through combine the heaven compensation to the crane control system we can easily eliminate the motion interference because of the wind or waves in the sea.

2.5 Anti-sway control

Anti-sway is to reduce the load sway which caused by the crane movements or wave impacts. This is similar to the Active heaven compensation. The method is based on energy dissipation priciple. The concept is to dissipate the load kinematic and potential energy by steering the motion of the crane or the wire length. The crane tip will move toward the same direction of the load sway.

2.6 Manipulator kinematics

Kinematics is the geometry of pure motion to motion considered abstractly, without reference to force or mass. Engineers use kinematics in machines design. Although hidden in much of modern technology, kinematic mechanisms are important components of many technologies such as robots, automobiles, aircraft, satellites, and consumer electronics, as well as biomechanical prostheses. In physics, kinematics is part of the teaching of basic ideas of dynamics. Kinematics studies the motion of bodies without consideration of the forces or moments that cause the motion.[6]

Through the Denavit-Hartenberg table and calculate the jacobian matrix for the crane. The main control system of crane can also be built. The Denavit-Hartenberg parameters are the four parameters associated with a particular convention for attaching reference frames to the links of a spatial kinematic chain, or robot manipulator.

2.7 Finite element analysis

Finite elements analysis is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. Finite element analysis shows whether a product will break, wear out, or work the way it was designed. It is called analysis, but in the product development process, it is used to predict what is going to happen when the product is used.

FEA works by breaking down a real object into a large number of finite elements, such as little cubs. Mathematical equations help predict the behavior of each element. A computer then adds up all the individual behaviors to predict the behavior of the actual objects.

Finite element analysis helps predict the behavior of products affected by many physical effects.[7]

3 MODELLING OF OFFSHORE HYDRAULIC CRANE

Modelling of an offshore hydraulic crane includes 3Dmodel , control systems, and hydraulic systems. AHC and anti-sway control modelling are also shown in this chapter. Here is a simple control structure figure of the offshore hydraulic system.

The control system was programed based on kinematic method and used to dispose the signal come from the signal source(pay load motion, crane tip motion etc). The 3D model of the offshore crane will provide the feedback signal to the control system to continue the operation.

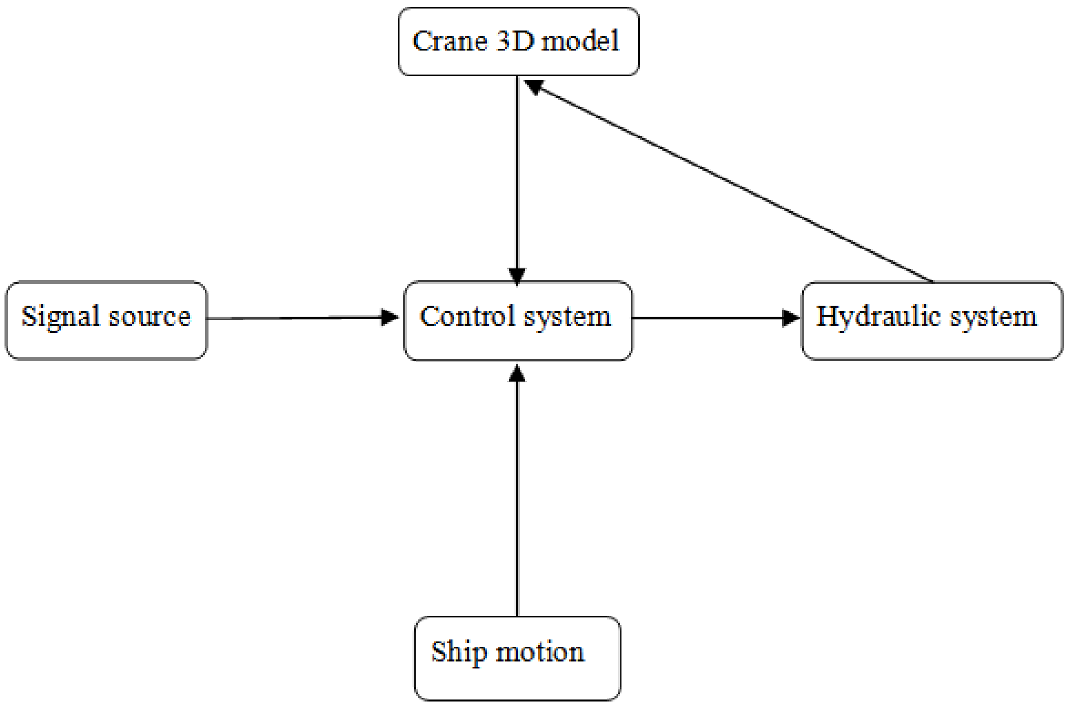


Figure 3.1.1 The control system structure

This figure shows the structure of the control system in my work. We provide the signal source like the velocity of the payload and the position of the crane tip etc. Then the control system will analysis and calculate the signal sources and the ship motion signal which comes from the sensor in the ship. After finished calculate the system will send the operate signal to the hydraulic system to drive it. The hydraulic system will send feedback signal to the control system to adjust the calculate result.

(Because of the joystick cannot use in the simulationX. I try to use the slider control and the functions as the signal sources in the simulation part.)

3.1 3D mechanical modelling

SimualtionX provides 3D animation and modelling toolbox for visual simulation. The .STL, .DXF or .LWO formats which are supported by most 3D CAD software can be imported into the 3D animation window easily. We also can edit the inertia and geometry of the mechanical model in the simulation edit page. The connections between parts are also based on the hieratical reference frames. The parts contains mass and inertia parameters and the joints have spring and damping. However we can also bulit a new model use the components library in the simulationX.

3.2 Crane model

Siemens NX software is an integrated product design, engineering and manufacturing solution. Advanced solutions for conceptual design, 3D modelling and documentation. Multi-discipline simulation for structural, motion, thermal, flow and multi-physics applications. Complete part manufacturing solutions for tooling, machining and quality inspection. The model created in Solidworks is defined by its physical properties and mechanical connections. During modelling of the crane in the NX we can do FEM analysis to check if the structure is reasonable. I also try to reduce the mass of crane to reduce the cost and the load of the hydraculic system.

Here is a complete structure of offshore hydraulic crane in the NX8.5. the main diamentions of the crane will provide in the appendix A.

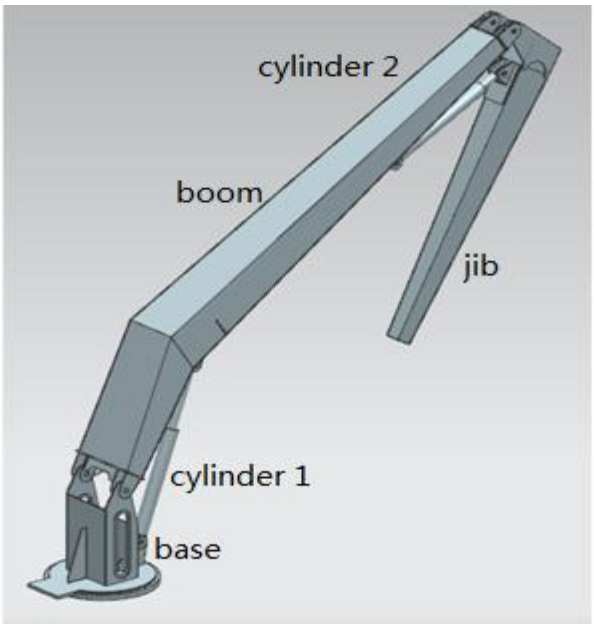


Figure 3.2.1 3D model of offshore crane

3.3 SimulationX 3D Mechanics Editor

3D Mechanic Editor in the simualtionX. The model created in NX can generate models to simulationX use the components in MBS mechanics library. The structure of the model mainly consists of bodies and joints, in addition with actuators and sensors.

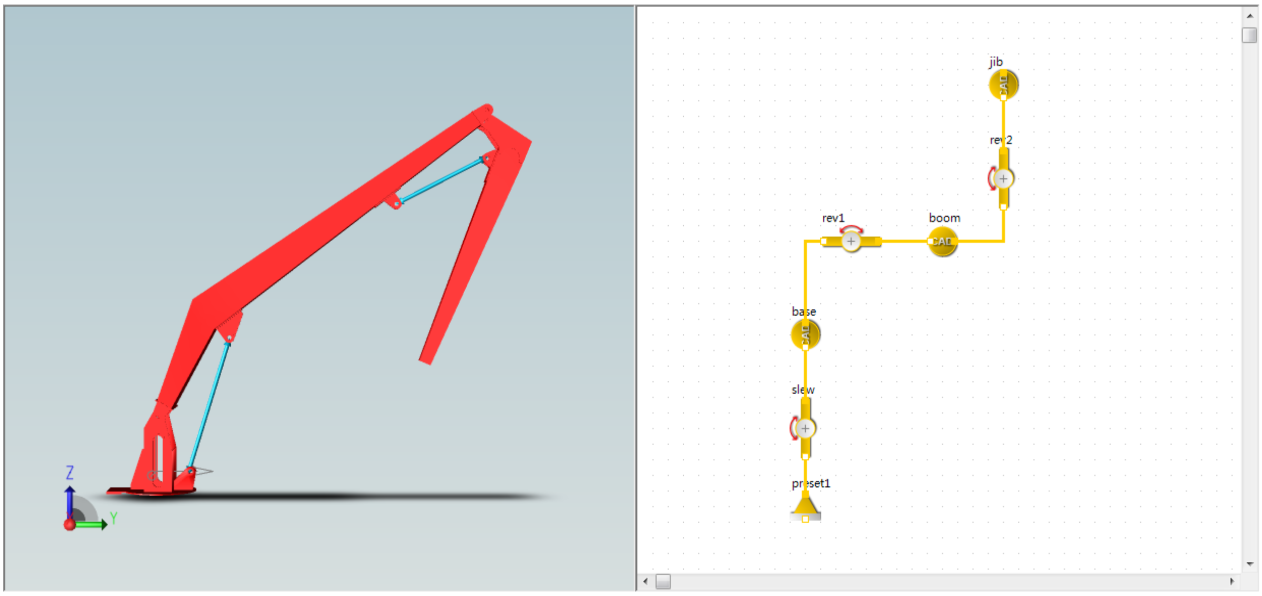


Figure 1.3.1 Crane model in simulationX and its components structure

The component preset1 in the figure is the constrain of the crane basement and in this components we can define the motion to simulate the ship motion during crane operation. The components rev1 and rev2 are the rotation constrains of the crane joints. In these components we can define the rotation constrain and limitation of the crane joints.

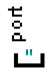
After importing the 3D model in the simulationX, the main actors in these rigid bodies are defined by their masses and inertias. The 3D models of the main components are created and exported from NX 8.5. The motion of each component is realized by controlling the corresponding reference frames. Therefore, the first step of inserting a new component is creating a reference frame. Then, insert the component in the frame and move it to the right position. Normally, the joint axis which the part should rotate align should be concentric with an axis of the frame. Also, every time inserting a reference frame, one axis the frame should be concentric with one of the previous part joint axis (which the component in this frame should be rotated with). For the reason that each part is rotated with previous part

simultaneously, the reference frame of a new component should be under the previous frame and the models of components should be inserted from base to jib step by step.
After i first finished import and built the crane model in the simualtionX i notice a problem. I define the crane rotation controlled by joint. However in the real situation the joints rotate because of the cylinder pistion move. So we should change the crane model from joint control to cylinder control. This wrok I have finished in the crane operation model. (this model will add in the CD and hand in with the thesis report)

3.4 Hydraulic system modelling

SimulationX provides hydraulic components library for modelling and simulating hydraulic systems. But the library does not contain all the components of the crane's hydraulic system. So we bulit our own library for the hydraulic components based on the hydraulic systems of the crane. In the simulationX we use typedesigner to make new components. The componenets I have made is the compensator and three control models to do the AHC and anti-sway. The program code will put in the appendix also.
We focus on modelling and simulation of the following hydraulic systems. The slew tower , main derrick ,elbow derrick and winch.
Because there are a lot of componenets we need to use in the hudraulic systems the main parameters setting and explain will be introduced in this part. Here i only introduce the mian parameters and functions of the hydraulic components in the hydraulic model of the simulationX. I skip the introduction of rest components in the system. Because they are easier to set compare to those I have introduced.

TANK



Tank is used for modelling of a hydraulic fluid reservoir.

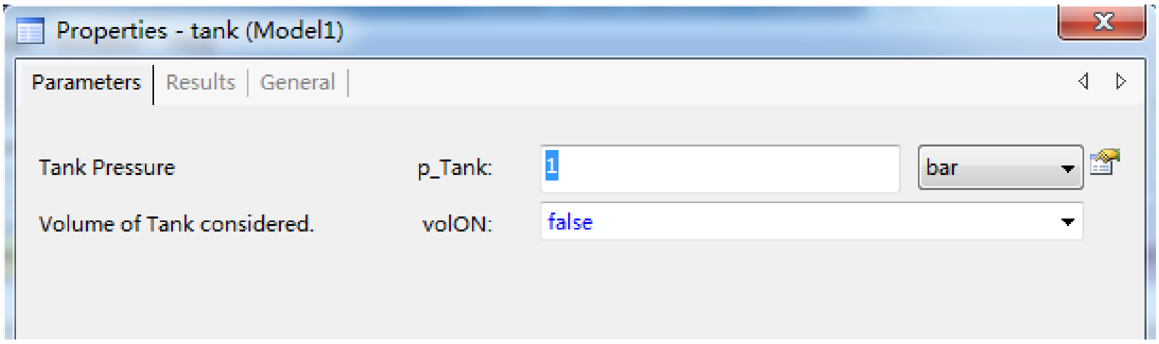
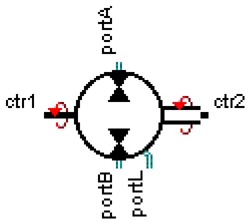


Figure 3.4.1 Tank properties

The mian parameters of tank is only tank pressure and weather consider the volume. I set the pressure 1 bar the same as the atmospheric pressure. We don't consider the volume of the tank.

Constant Displacement Pump/Motor



The Constant Displacement Pump/Motor is used for modelling of hydro-static displacement units. Since the element has two mechanical connectors (for shaft and housing), it can be integrated into arbitrary mechanical structures. For example, an elastically mounted housing can be modelled this way. Additional to the transfer of hydraulic into mechanical energy and geometric features (displacement volume), also friction and leakage losses can be considered optionally. The element may operate both as pump or motor.

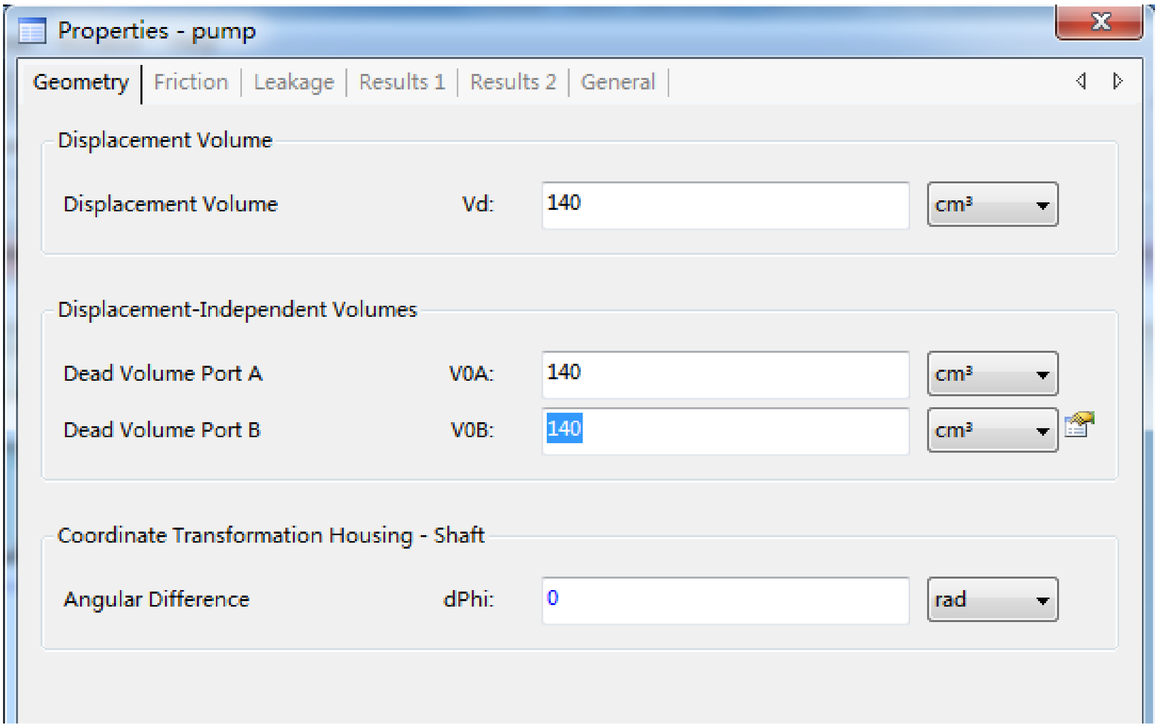


Figure 3.4.2 Pump properties

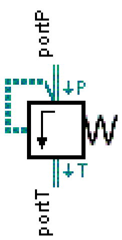
The main parameters are displacement volume and dead volume. The angular difference is used for calculate the rotation speed. We set this value 0. The volumes at Port A and B are calculated as:

$$V_A = V_{0A} + \left(\frac{V_d}{2}\right)$$

$$V_B = V_{0B} + \left(\frac{V_d}{2}\right)$$

Where the V_{0A} and V_{0B} are the dead volumes at Port A and B and V_d is the displacement volume. The volumes at port A and B are written to the hydraulic ports. The hydraulic connections read this values and calculate a total volume.

Pressure relief valve



The pressure relief valve can be used for modelling of direct-operated pressure relief valves with unrelieved outlet pressure. The main purpose of such a valve is to limit the maximum pressure in the connected volume at port P by opening the connection between port P and T if the pressure difference from P to T is above the set pressure.

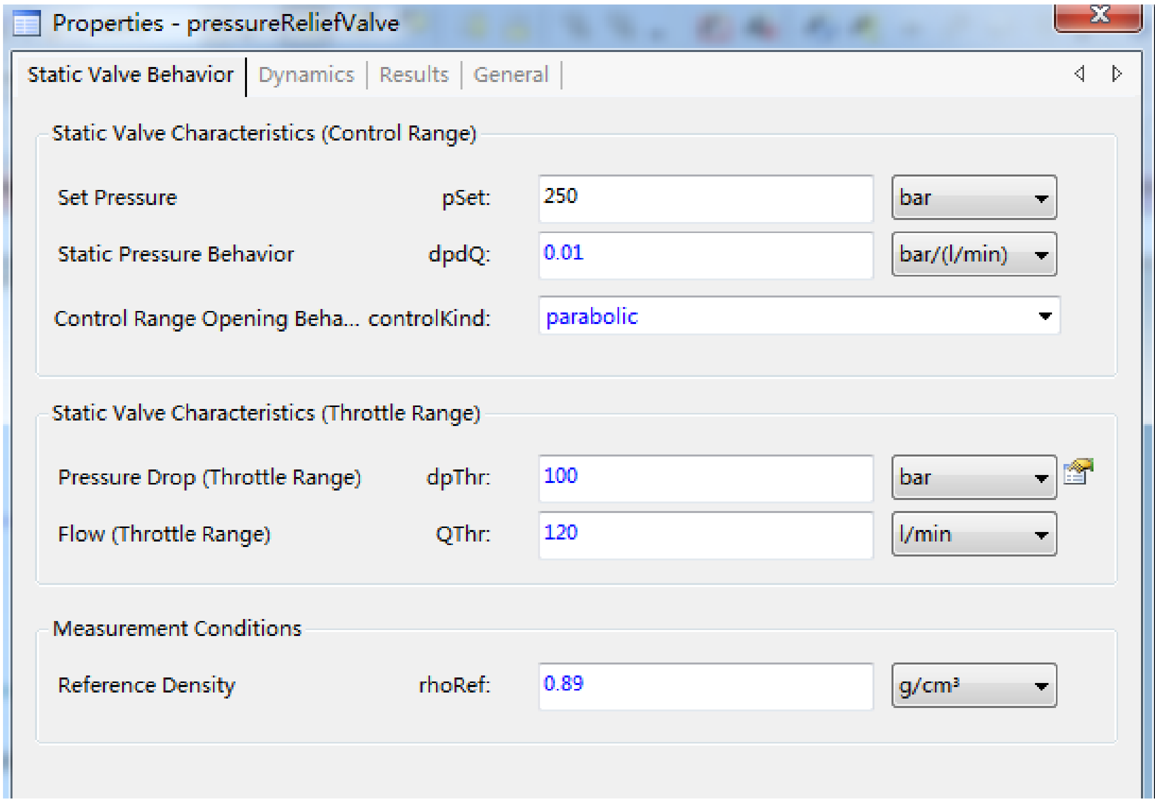


Figure 3.4.3 Properties of pressure relief valve

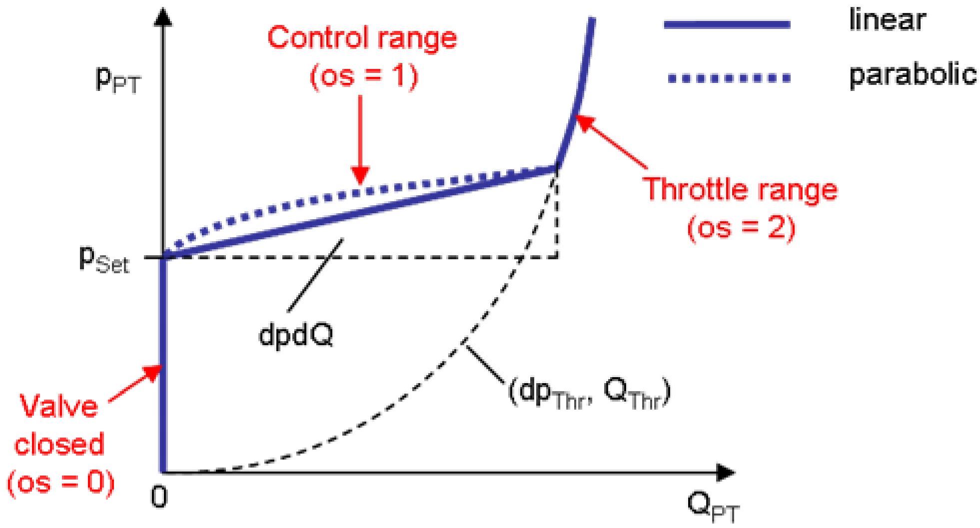
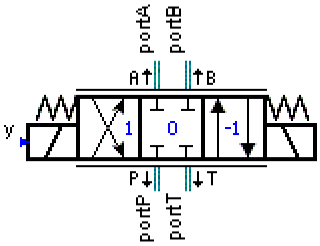


Figure 3.4.4 Static valve behavior and operating states of pressure relief valve

Set pressure is used for set the valve opertion pressure. Static pressure behavior is the Static pressure rise in the control range. There are two kinds of control range opening behavior parabolic and linear. This define how the flow increase when the pressure reachs to the operate pressure and continue to increase.

Static valve characteristics define the flow behavior in the throttle range. The last one is the reference density. The figure above is the line of static valve behavior and operating states. The X-axis is the volume and the Y-axis is the pressure. Before the pressure reach the set value the valve is closed (os=0). When reach the set pressure the valve open and volume start to increase with the pressure increase(os=1). When reach the throttle range the relationship between volume and pressure is shown as the line (os=2).

4/3 Proportional Directional Control Valve



This type of valves is used to start, stop and change the direction of flow by the pilot control. The hydraulic activated valve is driven by a small electrical operated pilot valve which is comparatively cheap for saving money.

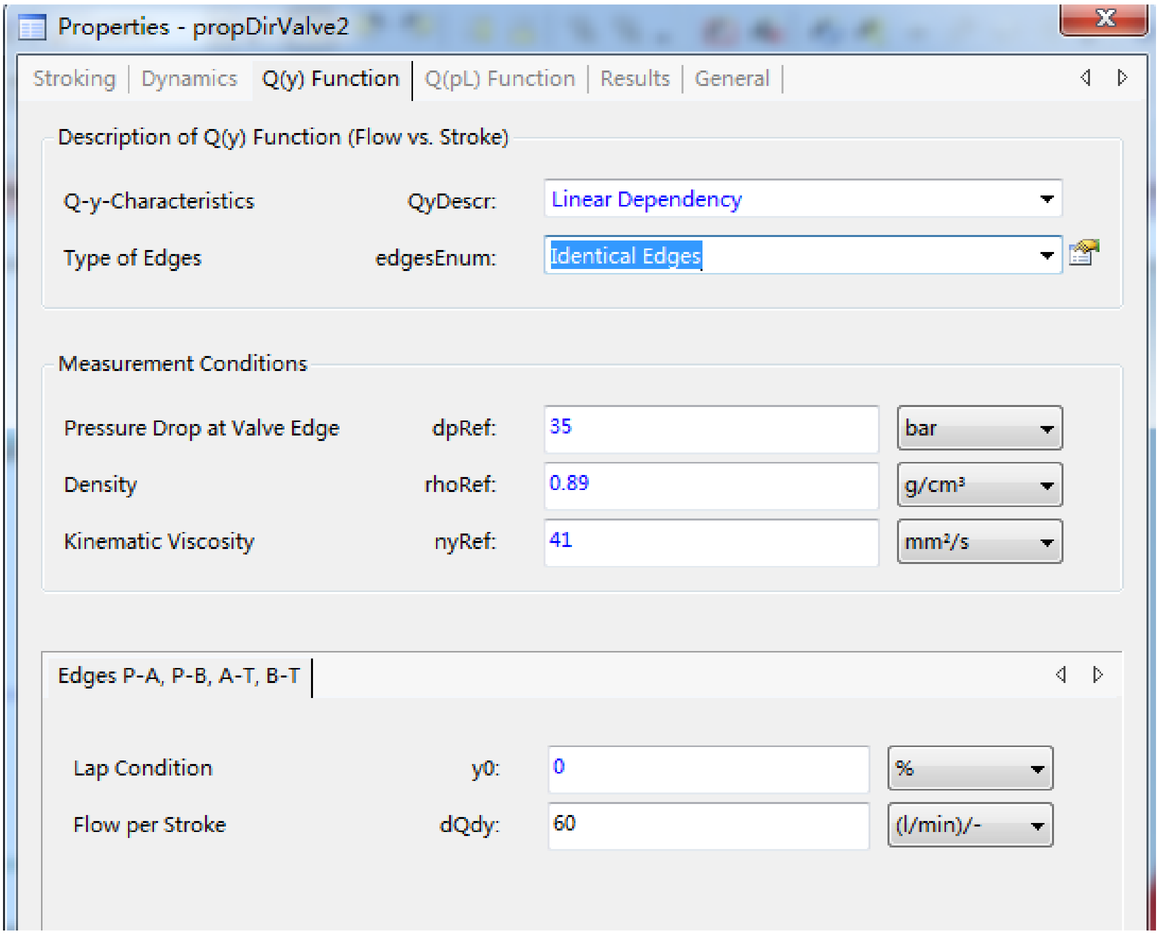


Figure 3.4.5 the direction control valve properties

There are many parameters need to set in this model. In the stroking label we need define the stroking function relates to the input signal Y to the stroke signal Y_S (in %). I define the input signal in the range (-1...1). The stroke signal Y_S is equal to the input signal Y in that range.

In the function label the Q-y-characteristics is to define the relationship between the flow Q and the relative valve stroke y. In my hydraulic system i set all the Q-y-characteristics as linear dependency so the relationship between flow and valve stroke is linear.

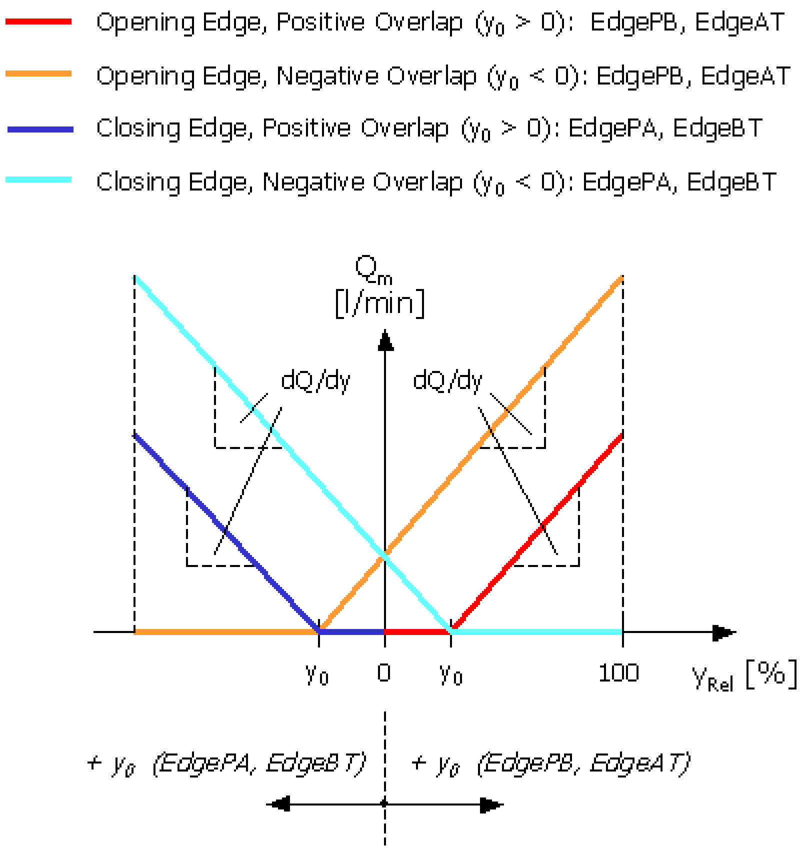
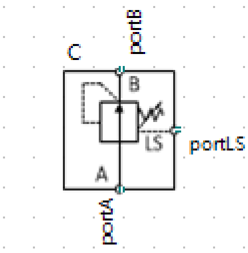


Figure 3.4.6 Flow of the valve description by linear dependency

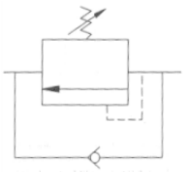
An Edge in this sense is represented by the variable flow restriction between two different ports of the valve. In general, there are two different kinds of edges: opening and closing. An opening edge is characterized by an increase of the flow cross section with increasing stroke signal. In opposite, a closing edge is characterized by a decrease of the flow cross section with increasing stroke signal.

compensator



Pressure compensators are used to maintain preset pressure differential across a hydraulic component to minimize the influence of pressure variation on a flow rate passing through the component. The installation of compensator in front of the 4/3 way valve could maintain a required pressure differential for the valve and the flow. Because this component is made by the typedesigner so we just set one parameter. The main parameter is the set pressure. The program code will put in the appendix.

Counterbalance valve



The counterbalance valve, also called a holding valve, is used to prevent a weight from falling uncontrollably. When the directional control valve is shifted, the system will unload unless there is a means for creating an opposing hydraulic force. A counterbalance valve accomplishes this task.

3.5 Slew tower hydraulic system modelling and simulation

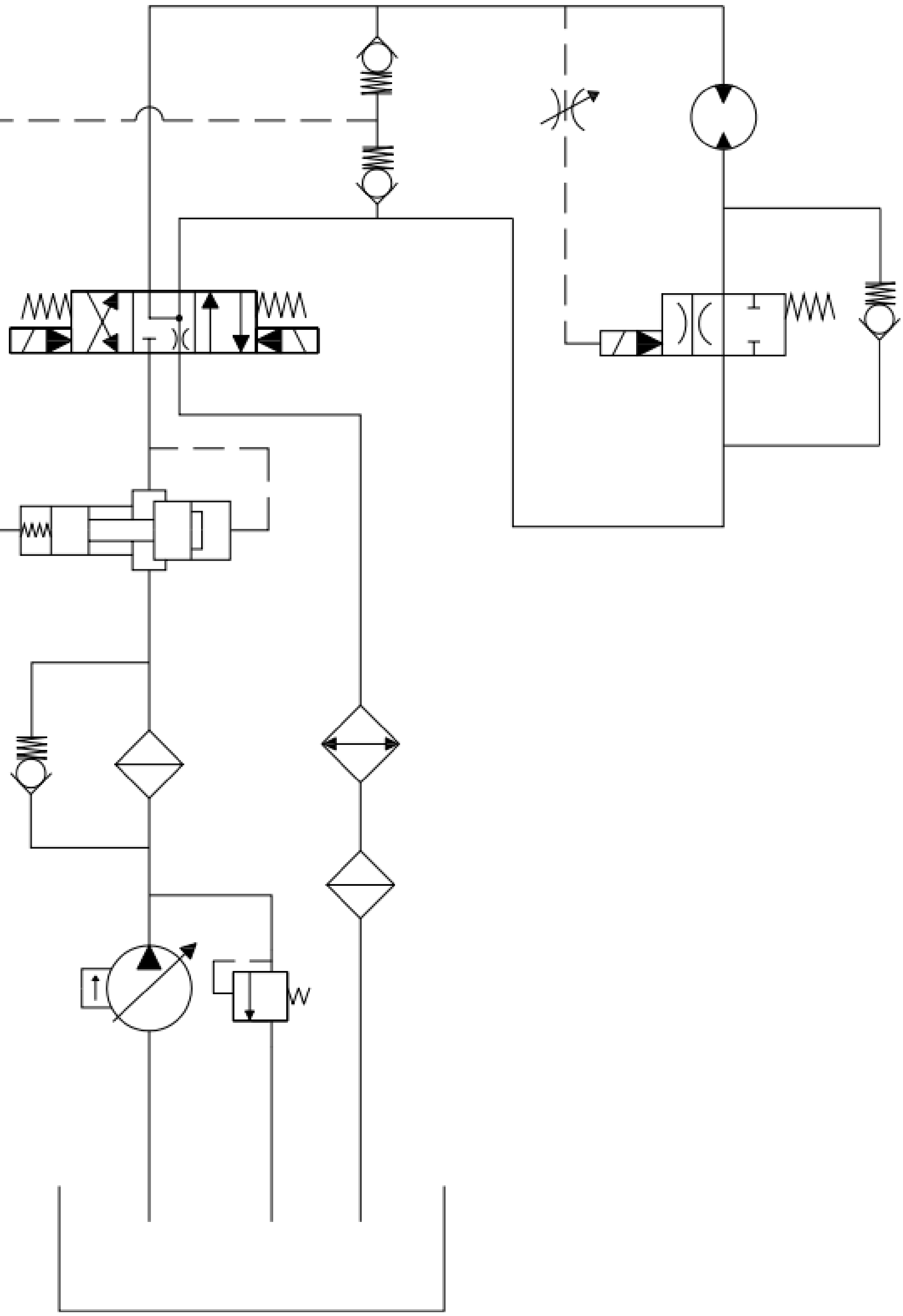


Figure 3.5.1 Simplified slew tower hydraulic system

Main parameters of components in the system

Pressure compensated pump	Displacement volume 140 cm^3 ,speed 1800rpm, maximum pressure 300bar.
Compensator	Pressure set point at 30bar
Direction control valve	Maxinmum flow 120l/min
Hydraulic motor	Motor displacement 630cm^3
Gera box	Gear ratio 190
Tank	Pressure 1bar

Based on the simplified model we can model the hydraulic system of the slew ring control system. All the parameters were adjusted according to the calculated based on the crane operation requirments.

According to the crane operation requirments. The require rotation speed of the slew ring is $\omega = 60\mathrm{s/rev}$. The displacement of the hydraulic motor is $\forall$=160cm^3. Flow through the motor is $\mathrm{Q} = 120\mathrm{l/min}$. So the gearbox ratio is calculated by:

$$n = \frac{\omega}{\frac{\forall}{Q}} = \frac{60}{\frac{0.63}{120/60}} = 190$$

Simulation X modelling

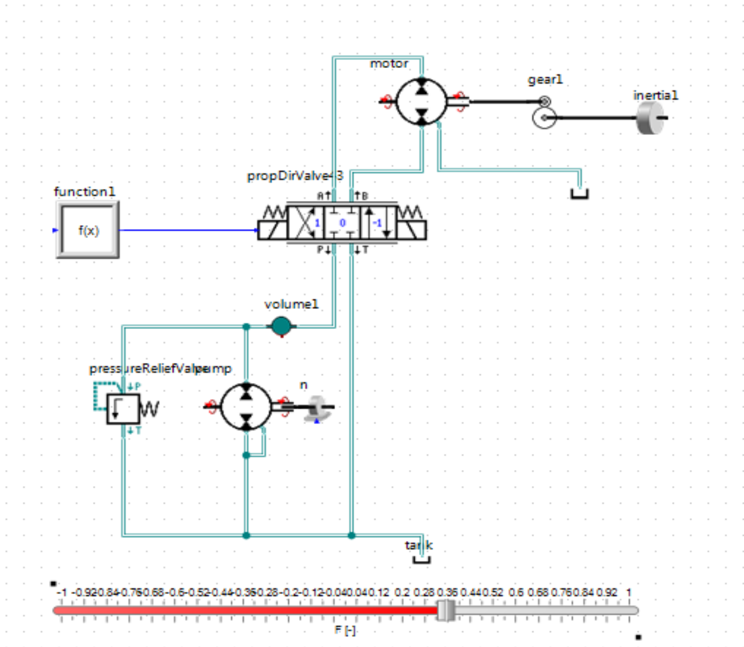


Figure 3.5.2 Simplified slew tower hydraulic system simulation model

Hydraulic system plots

All the variables of the hydraulic system reaction can be plotted in simulationX. I just show the plots of the slew ring here.

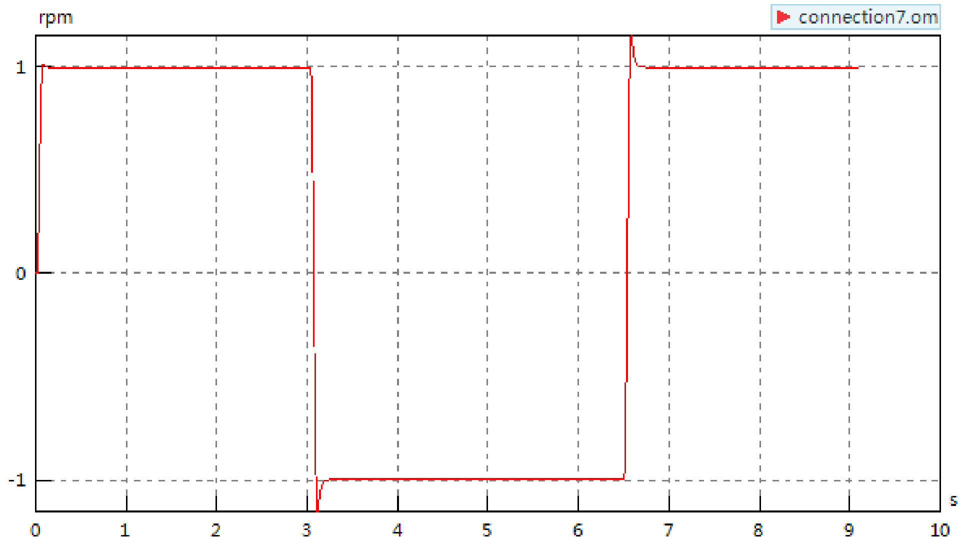


Figure 3.5.3 Slew angle plot

From this plot, we can see the rotation speed of the slew ring during the operation. I didn't set rotate limitation of the slewring. So it can rotate 360 degree. The X-axis is the time and the Y-axis is the rotation speed of the slewring. The slew speed keep stable at 1 rpm/s and changed to -1 rpm/s when i changed the valve direction at aroud 3s.

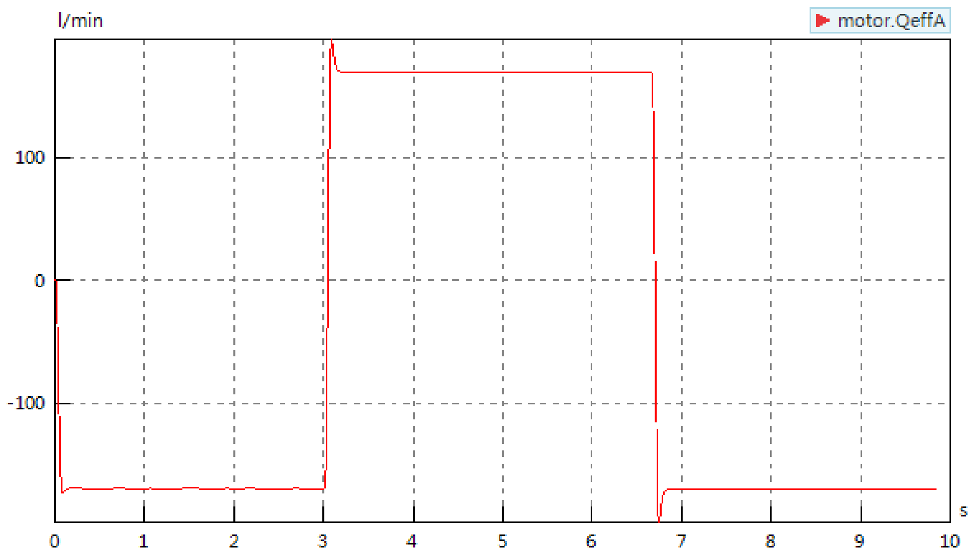


Figure 3.5.4 Slew motor flow plot

From the plot we can see the flow through the motor during the operation. The X-axis is the time and the Y-axis is the flow. Motor flow keep stable around $\pm$180l/min in two different rotate directions.

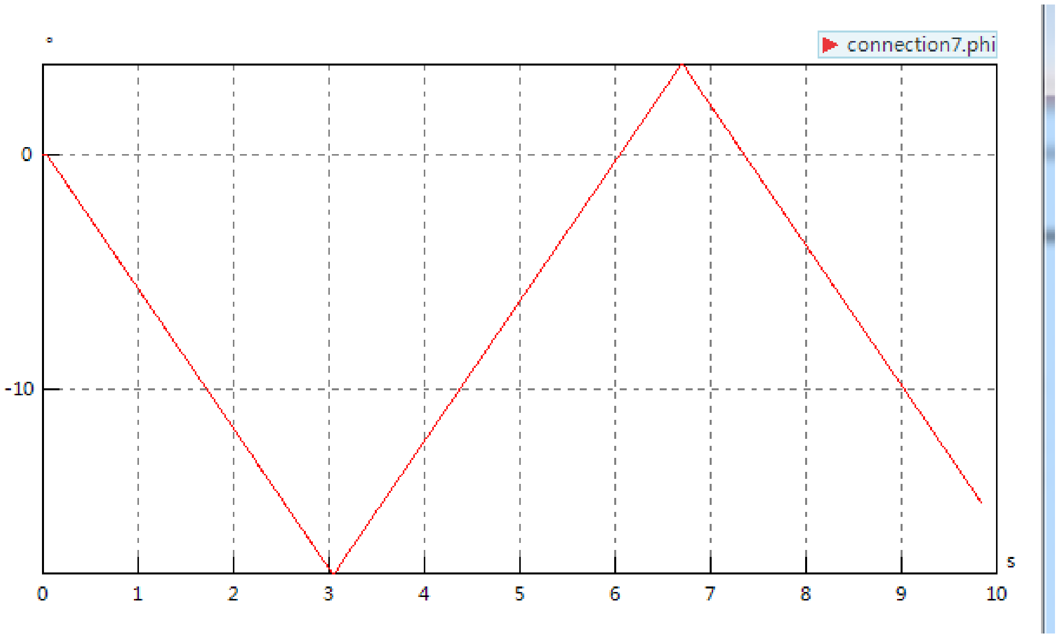


Figure 3.5.5 Slew angle plot

Plot shows angle in degrees. The X-axis is the time and the Y-axis is the degress of angle. I didn't set rotate limitation of the slew ring. So the rortate direction controled by the valve direction. We can see the reaction time of the motor is very short that means the torque of the motor is big enough to drive the system.

3.6 Main derric hydraulic system modelling and simulation

Through the mechanical calculate based on the kinematics method we can get the joint force of the crane. And the requirment load of the cylinder. The detail calculate part will add in the appendix C.

Total force at base- boom joint calcuate from the jacobian:

$$\vec{F}_{BB} = \vec{F}_{cyl1} + \vec{F}_{SWL} = \sqrt{\left(\sin\theta * F_{cyl1}\right)^2 + \left(\cos\theta * F_{cyl1} - SWL\right)^2} = 1169KN$$

Main parameters of components of the system

Pressure compensated pump	Displacement 140 cm^3 ,speed 1800 rpm, maximum pressure 300bar.
compensator	Pressure set point at 30bar
Direction control valve	Maximum flow 140l/min
Chydraulic cylinder	Maximum stroke 1710mm , piston diameter 220mm , rod diameter 180mm.
Tank	Pressure 1bar

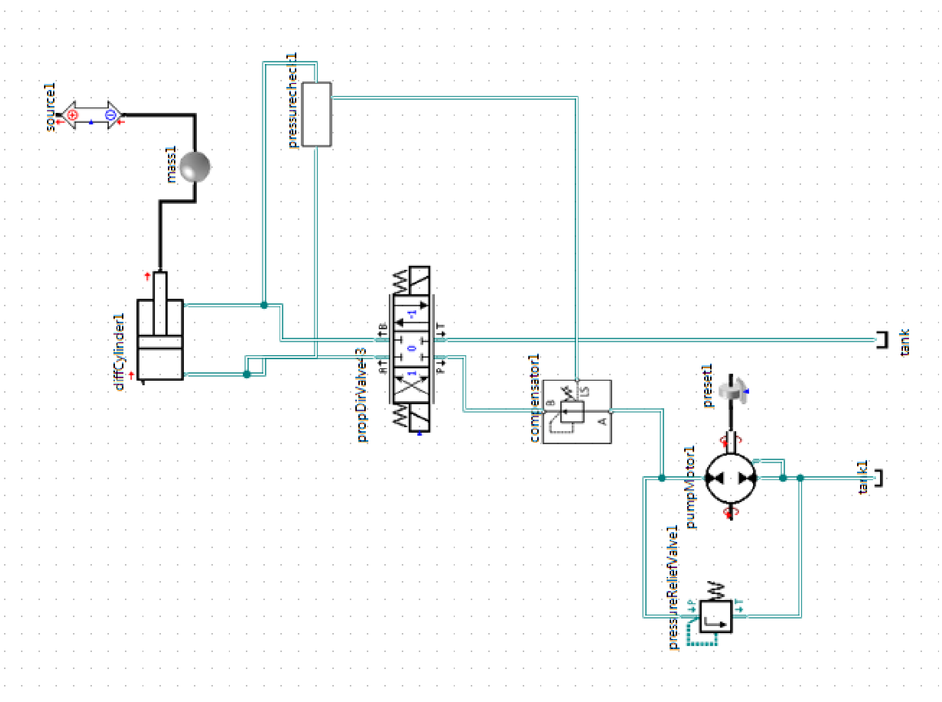


Figure 3.6.1 Simplified cylinder control model in simulationX

Here is the original cylinder control model in simulationX. Both of the main derrik cylinder and elbow cylinder derrick are built based on this .The pressure check component in the model is built for select the higher pressures between two pipes connect to the cylinder.

Hydraulic system plots

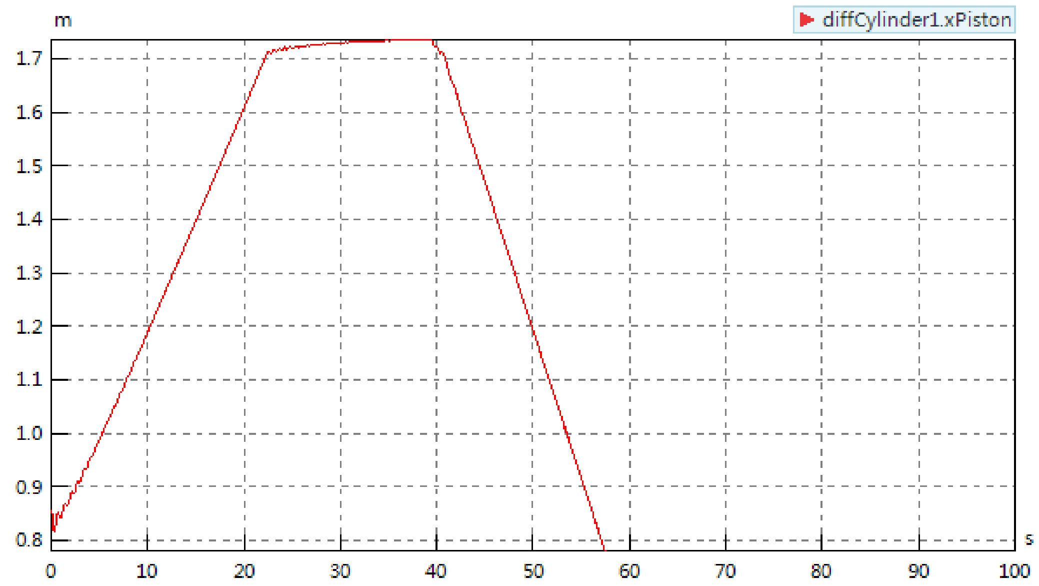


Figure 3.6.2 The cylinder position plot

The X-axis is the time and the Y-axis is the position of cyinder piston in meters. We defined the cylinder stroke at 1710mm. Through the plot we can see the cylinder stoppted when reaching the limitation at 23s. After about 20 second the pistion of the cylinder start to go back to other direction.

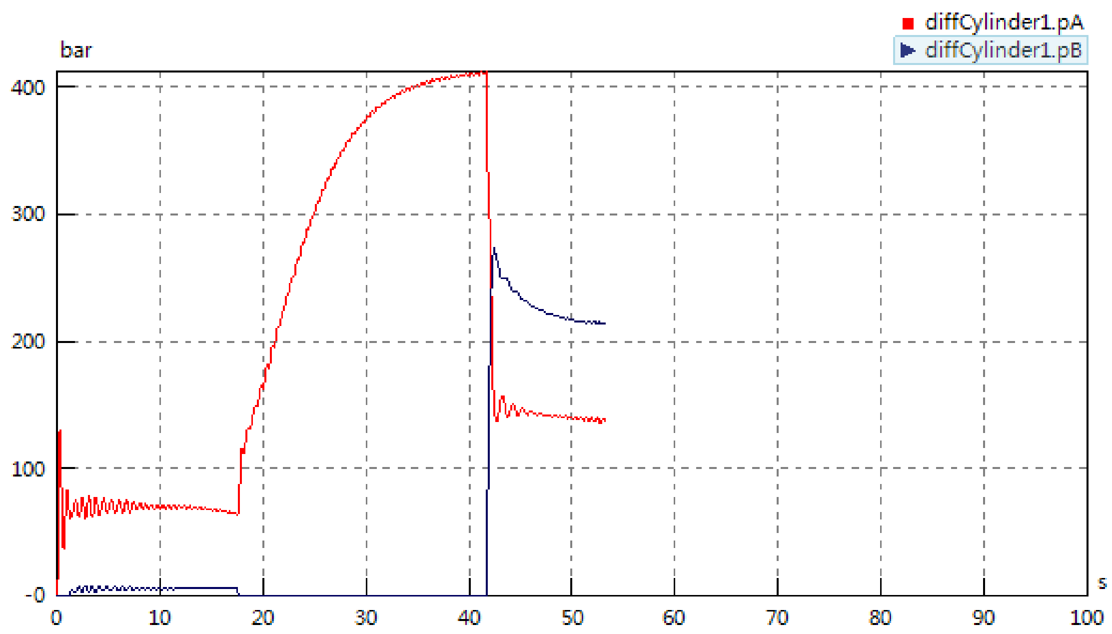


Figure 3.6.3 The cylinder pressure plot

A chamber pressure (red line) represents the pressurre at the piston side of the cylinder. B chamber pressure (blue line) represents the pressure at the rod side of the cylinder. At about 17s the pressure increased because the cylinder has been fully extend.

3.7 Elbow derrick cylinder hydraulic modelling and simulation

Main parameters of components of the system

Pressure compensated pump	Displacement 140 cm^3 ,speed 1800 rpm, maximum pressure 300bar.
compensator	Pressure set point at 30bar
Direction control valve	Maximum flow 140l/min
Chydraulic cylinder	Maximum stroke 1710mm , piston diameter 220mm , rod diameter 180mm.
Tank	Pressure 1bar

Total force at boom-jib joint

$$\vec{F}_{BJ} = \vec{F}_{cyl2} + \vec{F}_{SWL} = 1391\text{KN}$$

The calculation process of this result will put in the appendix.

Plots of elbow derrick cylinder system are similar to the main derrick cylinder system. We can also plot out the pressure, flow, and position of pistion etc.

3.8 Complete hydraulic system modelling and simulation including 3D model

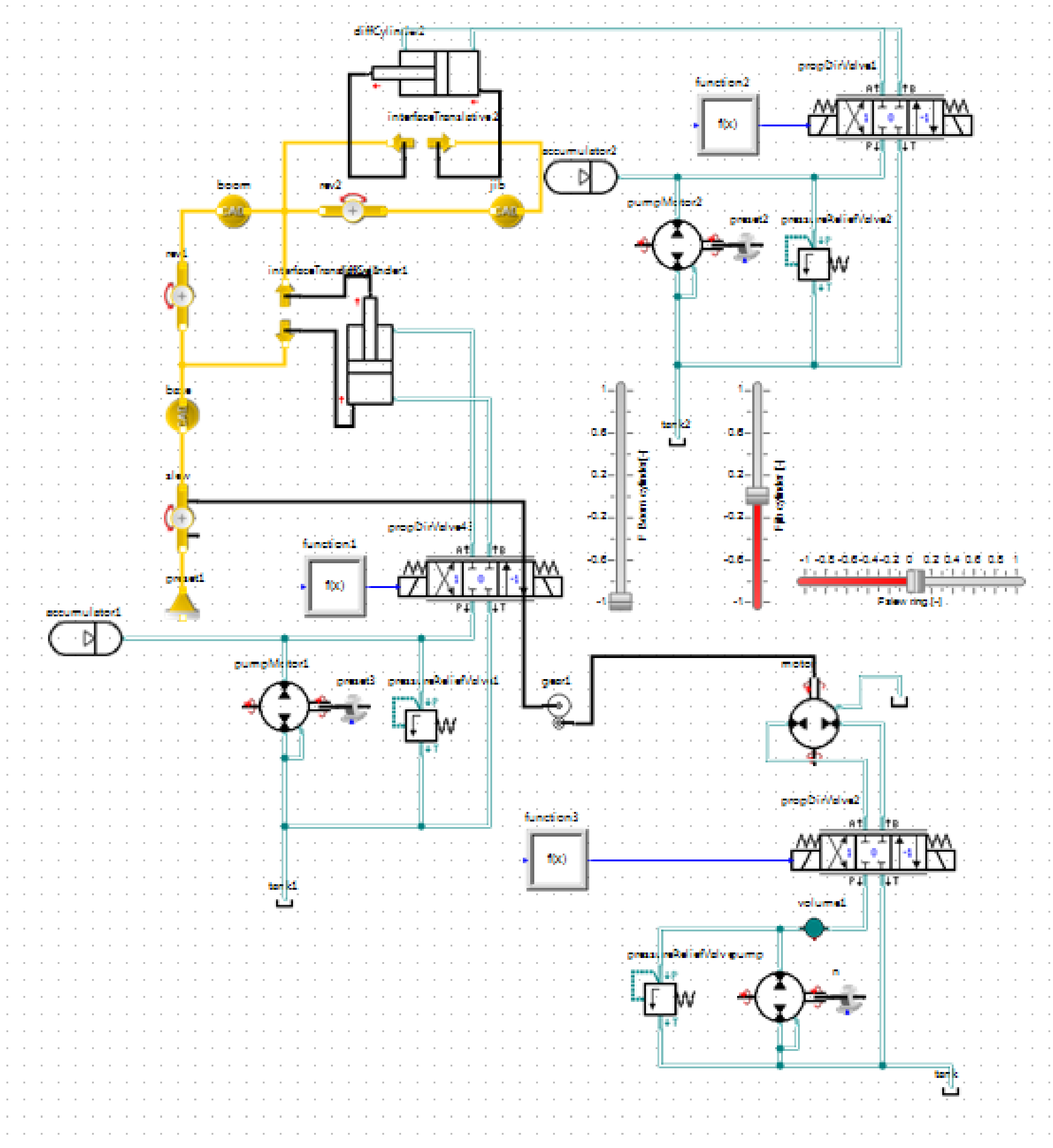


Figure 3.8.1 Control system figure with hydraulic system

Use the slider control to control the sub hydraulic system of the crane. Through this control system we can simulate the crane more close to the real life. At the previous work and study. We use the rotate actuators to control the joint of the crane. In this model we control the crane operated under the drive of the cylinders and pumps. Although the hydraulic system was simplified and all the models were modelled as ideal models, to achieve real time sumulation we still need to consider the following cases:

The initial values of the hydraulic system. For instance the pressure in the pipe before the actuators.

Fluid compressibility is given by the bulk modulus of the fluid. Fluid compressibility in thin walled pipes are taken into account through the definition of an equivalent bulk modulus.[7]

The systen will fluctuates at the beginning period of the simulaiton because of the impact of the hydraulic system. So when you analysis the plots or program a control system. Consider this case and try to fix that problem.

Simulaiton results

The following simulaiton results are ploted to show the working situation fo the crane system. So this is just pick up some variables and parameter as examples. For detailed study of the specific components or performance of the system. We can also add new plots for the other components.

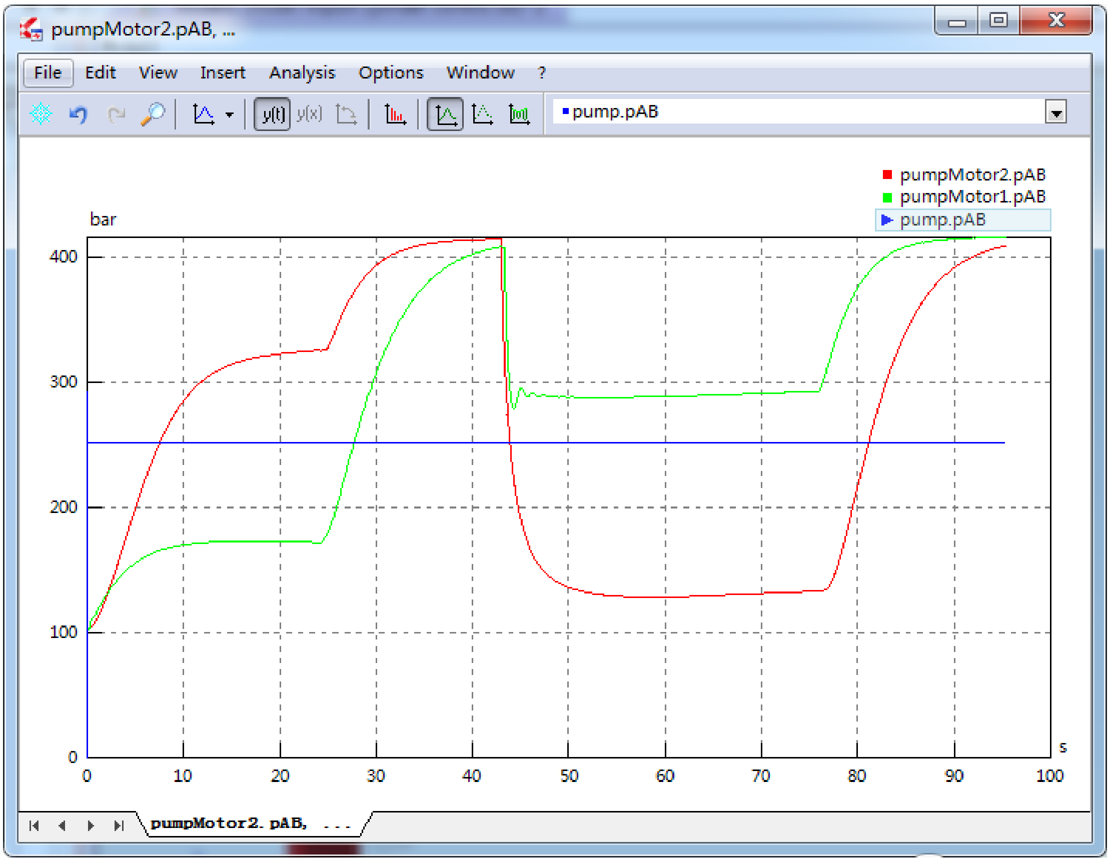


Figure 3.8.2 The pressure of the crane hydraulic system

I operate the crane to its extreme position then reload it. The X-axis is the time and the Y-axis is the pressure in bars. Red line represents the pump pressure of the main derrick pump. Green line represents the pressure of the elbow derrick pump. Blue line represents the pump *pressure of slew ring. At about 43s the pressure increased because the cylinder has been fully extend. The slew ring is keep clockwise rotation so the pressure is stable about 250 bar.*

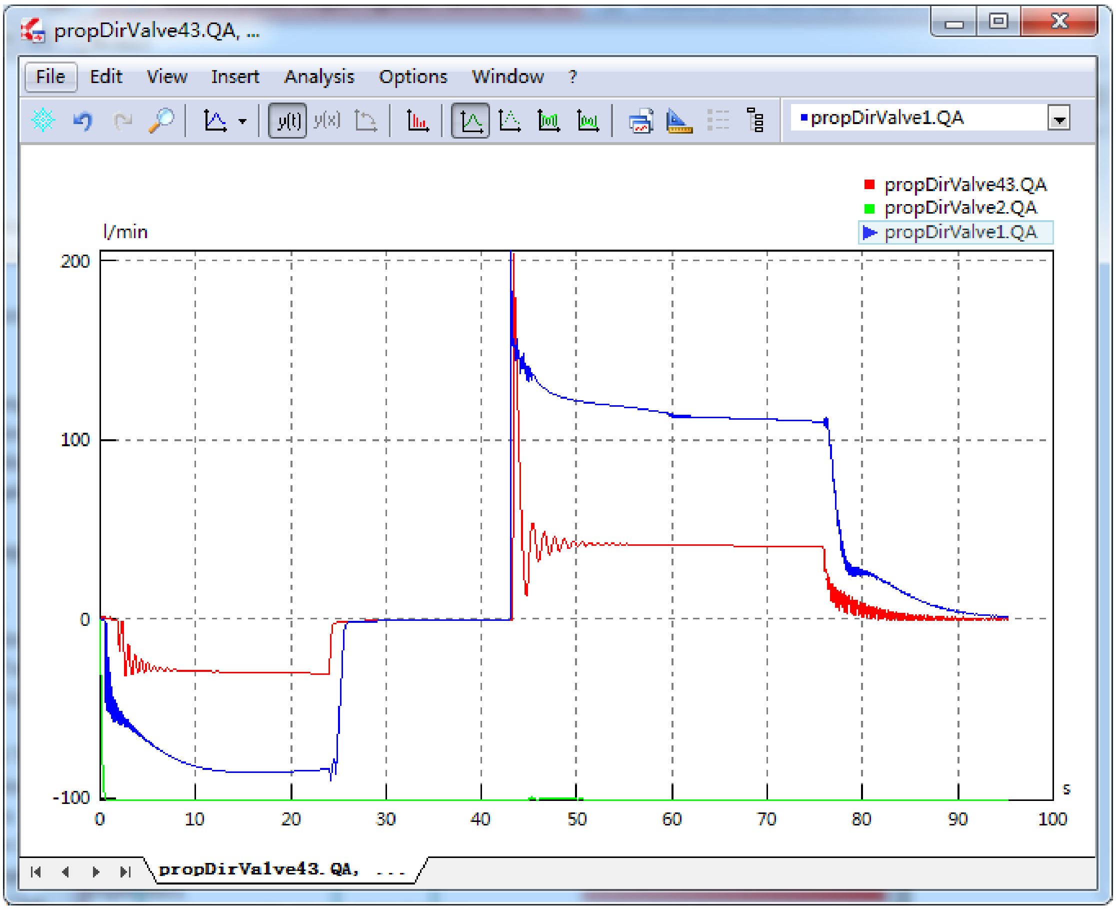


Figure 3.8.3 The flow in port A of direction control vale

I operate the crane to its extreme position then reload it. The X-axis is the time and the Y-axis is the flow in l/min. Red line represents the flow in port A of direction control valve in the main derrick cylinder. Blue line represents the flow in port A of direction control valve in the elbow derrick cylinder. Green line represents the flow in port a of direction control valve in the slew ring. The slew ring is keep clockwise rotation.

4 ACTIVE HEAVEN COMPENSATION CONTROL AND SIMULATION

In this part, we introduce the algorithm of active heaven compensation system and operation of offshore crane. There are three kinds of ways to achieve the heaven compensation. And in the simulationX i bulit all the three system models. But the secondary one “the heaven compensation of secondary side winch control” i just finished the modelling part.

As the control system structure figure shows(figure 3.1.1).Through the external signal sources from the crane driver and sensors in the crane. The heaven motions of the vessel can be compensated by adding the opposite heaven signals to the controller to drive the crane. All the three active heaven compensation system were bulit based on this working structure.

4.1 Normal primary winch control of AHC

The purpose of this normal primary winch control is to keep a load, held by equipment on a moving vessel, motionless with regard to the seabed or another vessel. Commercial offshore cranes usually use some method of motion detection to measure the current ship movement . In this project, the AHC is realized by the winch which means the winch generates the same velocity but in opposite direction with ship motion to compensate it.

PI controller

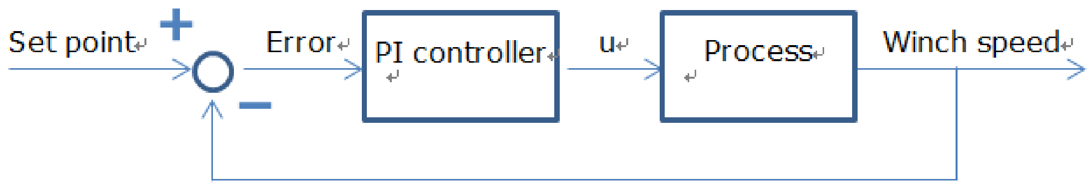


Figure 4.1.1 Block diagram of a PI controller in a feedback loop

In this system the set point was the input signal which represents the required winch speed. But in the new model with AHC, the set point is the sum of joystick signal and negative ship motion speed, and the error is:

$$u = K_p * \text{error} + K_i * \int \text{error}$$

Modelling and simulaiton in simulationX

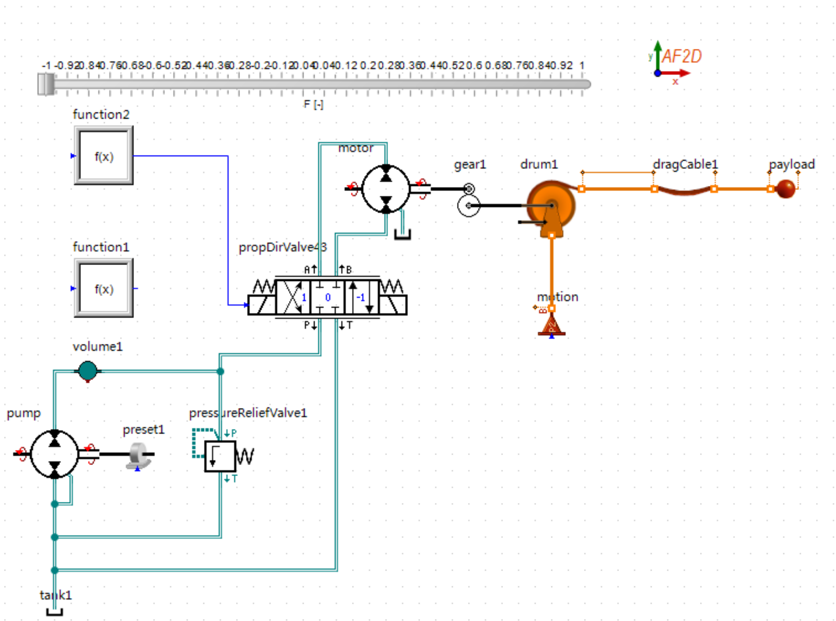


Figure 4.1.2 Normal winch control of active heaven compensation

This figure is the normal winch control hydraulic system. I use the slider control to control the velocity of the payload. The function 2 is control the direction control valve to control the flow of the system. The function 1 is works as a sensor to get the velocity of the payload and send the signal to the function 2.

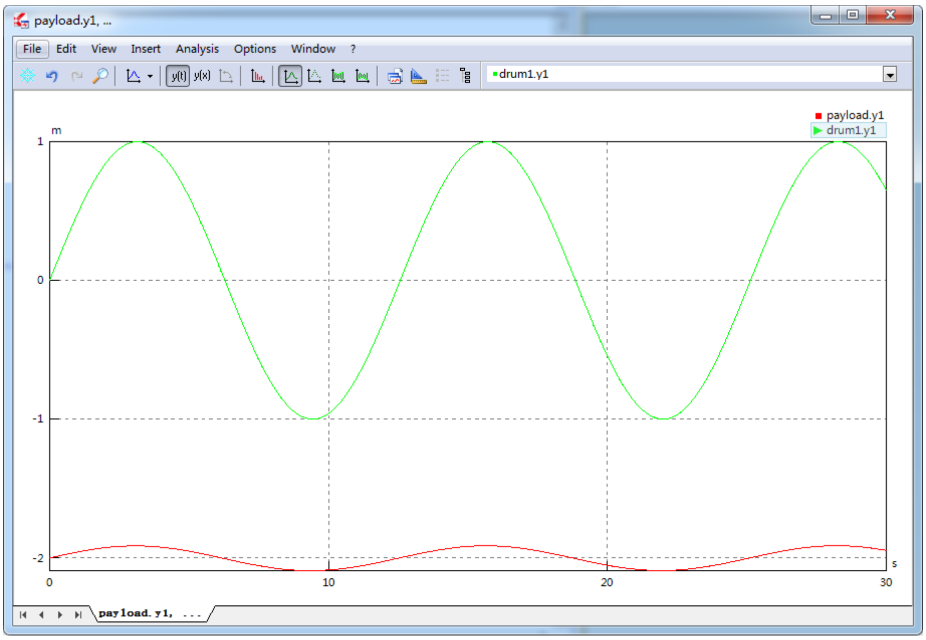


Figure 4.1.3 The displacement of the ship and payload

The X-axis is the time and the Y-axis is the displacement in meters. I set the payload velocity to zero. The red line is the displacement of the payload. The green line is the displacement of the winch. The winch simulates the ship motion. We can see the payload can keep stable when the ship is moving up and down because of the AHC.

4.2 The secondary side winch control of AHC

The normal primary winch control to do the active heaven compensation is not realy used in the crane design. Because to move the winch drum back and forth, the pump will have to build up pressure on one of the sides , creating torque in one direction. When the control system detects that movement in the other direction is needed, the pump will have to reduce pressure on one side and increase it on the other side. This force the pump to work against the hydraulic spring every time when a change in rotational speed or direction is needed. This cause a significant delay in the efforts to control the winch drum motion.
So in this chapter we use a new AHC control system to do it. This called the secondary control. Secondary control means that the system is controlled on the “secondary side” winch despite the name is the place which is closest to where the actuation is needed, in other words , closest to the winch drum. This means that the control is taking place where it matters , directly in mechanical contact with the drum which gives excellent control of the wire movement.
In the secondary control , the motor fitted to the winch drum can alter its displacement. That means it will constantly change the size of itself, and thereby controlling the torque it creats and the flow it needs. This is done by controlling the swash-plate-angle of the axial piston motor. The motors can change the displacement between +1 and -1 meaning craeting full torque in both directions.[8]
The secondary control motor always uses the same inlet port which means that the pump will only have to keep a constant pressure during operation. This also means that the pump is less expensive.

Modelling and simulaiton in simulationX

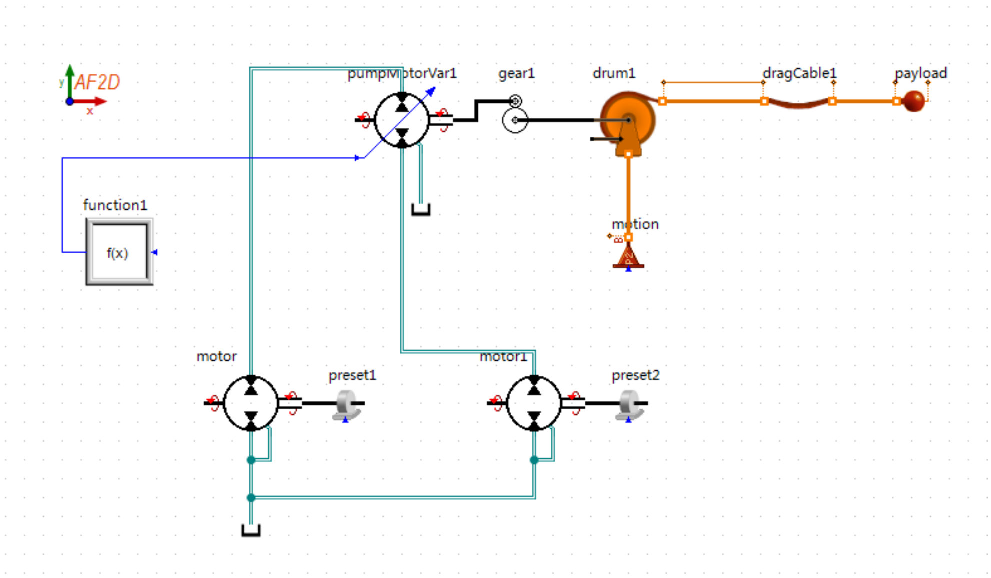


Figure 4.2.1 The secondary winch control system in simulationX

This is the hydraulic system model of the secondary winch control. The pump in the left side is the low pressure pump. This pump is use to hold the pressure in the system. Use the function as a singal source to control the variable displacement motor.

4.3 Kinematics control of AHC

This part is the active heaven compensation through the kinematics method. The concept is through solving the kinematic model of the crane structure to control the crane. We control the crane tip motion throuth the signal source. Then computing the kinematics to get the cylinder velocities to control the crane. Joint and angles and vessel motions can get through the sensors. If the crane tip can keep still during the ship motion then there will not have any heaven of the payload.

The coordinate system comprises five sub-coordinates representing the three revolute joints, the original coordinate and the jib end.

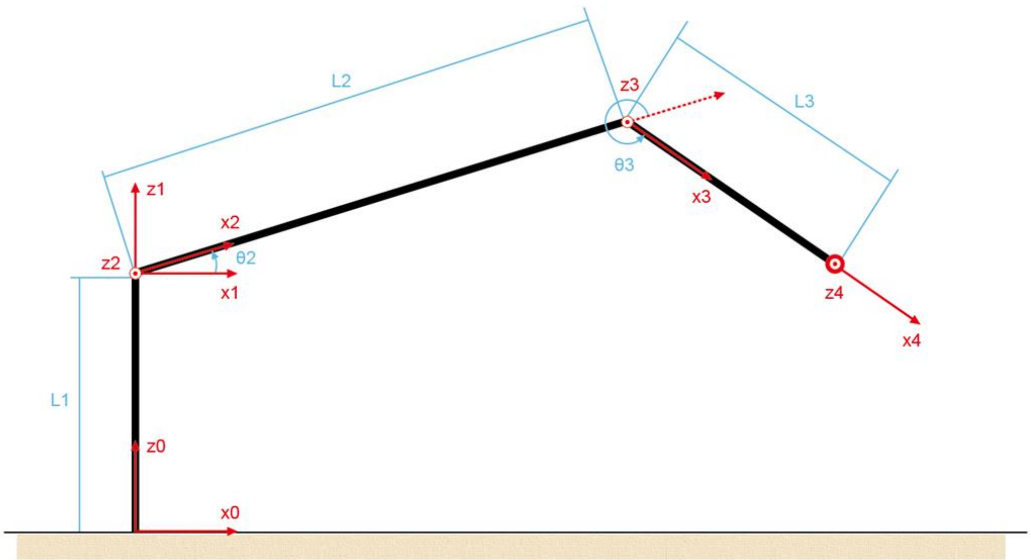


Figure 4.3.1 coordinate system of the crane

The rotations of the coordinate systems are according to the D-H method Li and θ_i (I = 1, 2, 3) are the link length and joint angles.

D-H table

The four parameters of D-H table are defined as following:

α_{i-1}: the offset angle from the z_{i-1} to z_i axis about x_{i-1}

a_{i-1}: the offset distance or the shortest distance from the z_{i-1} to z_i axes along x_{i-1}

θ_i: the offset angle from the x_{i-1} to x_i axis about z_i

d_i: the distance from the x_{i-1} to x_i axis about z_i

	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	L_1	θ_1
2	0	90°	0	θ_2
3	L_2	0	0	θ_3
4	L_3	0	0	0

D-H table for the coordinate system

Transformation matrix

The transformation matrixes for each joint could be derived by the following equations with the corresponding D-H table.

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The transformation matrixes for each joint are shown below:

Joint 1:

$$ {}^{0}_{1}T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Joint 2:

$$ {}^{1}_{2}T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Joint 3:

$$ {}^{2}_{3}T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & L_2 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Joint 4:

$$ {}^{3}_{4}T = \begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Transformation matrix from frame 4 to frame 0

$$ {}^{0}_{4}T = {}^{0}_{1}T * {}^{1}_{2}T * {}^{2}_{3}T * {}^{3}_{4}T $$

Calculate and simplify the result to get the transformation matrix (kinematic equations) from the tip of the crane to the crane base:

$$ {}_4^0T = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} c1c23 & -c1s23 & s1 & L_3 * c1c23 + L_2 * c1c2 \\ s1c23 & -s1s23 & -c1 & L_3 * s1c23 + L_2 * s1c2 \\ s23 & c23 & 0 & L_3 * s23 + L_1 + L_2 * s2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$ is the crane tip position vector.

The static torques of each joint could be calculation by the Jacobian matrix.

The Jacobian is derived by propagation from link to link or simply calculating the derivation of the last column of transformation matrix. The Jacobian matrix of this crane is shown below.

$$ {}^0J(\theta) = \begin{bmatrix} -L_3s1c23 - L_2s1c2 & -L_3c1s23 - L_2c1s2 & -L_3c1s23 \\ L_3c1c23 + L_2c1c2 & -L_3s1s23 - L_2s1s2 & -L_3s1s23 \\ 0 & L_2c2 + L_3c23 & L_3c23 \end{bmatrix} $$

Then we can invert the matrix to calculate the joint velocities from arn tip velocities:

$$ \dot{\theta} = {}^0J(\theta)^{-1}\, {}^0V $$

The $\dot{\theta}$ is the vector of the joint angular velocities, ${}^0J(\theta)^{-1}$ is inverse of the jacobian matrix and mutiply this by the vector of arm tip cartesian velocities.

When we consider the kinematics method we must solve the problems of singularity points. Which determinate is zero that the jacobian is singular. In my system the result is shows in the following table:

	Minimm	Maximum	Radius
Base-boom joint	-3.33	87.44	-0.0581~1.5261
Boom-jib joint	180.93	333.70	3.1578~5.824

Modelling and simulaiton in simulationX

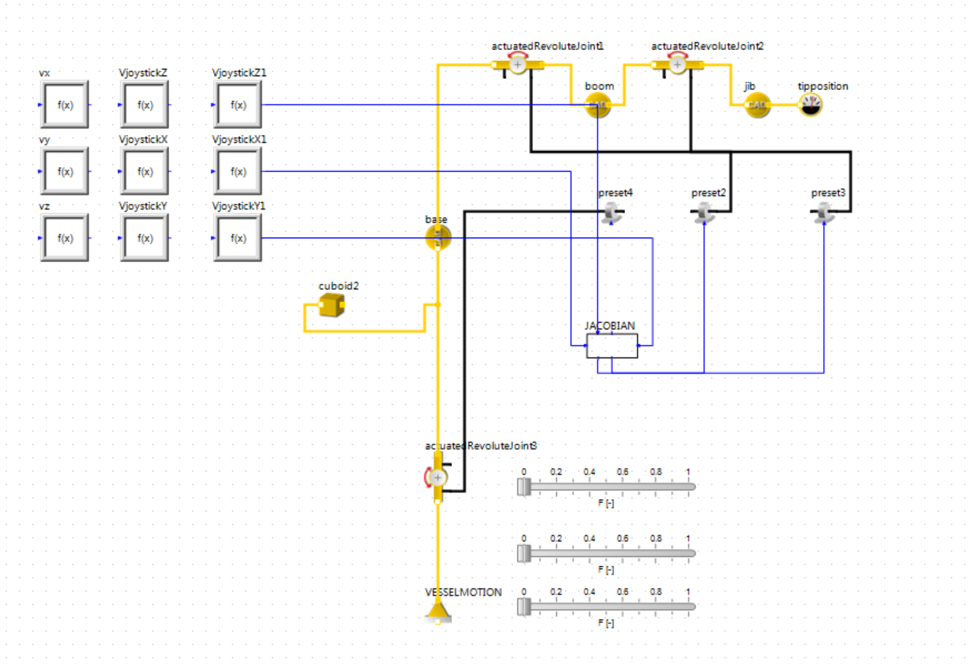


Figure 2.3.2 The active heaven compensation of kinematic control

This figure shows the structure of the active heaven compensation of kinematic control. Through the sensor which was installed on the crane tip. We get the velocity and displacement signal of the crane tip. Then send it to the control system. The calculate program in the control system(Jacobian) will send the control signals to the actuators in each joint of the crane.

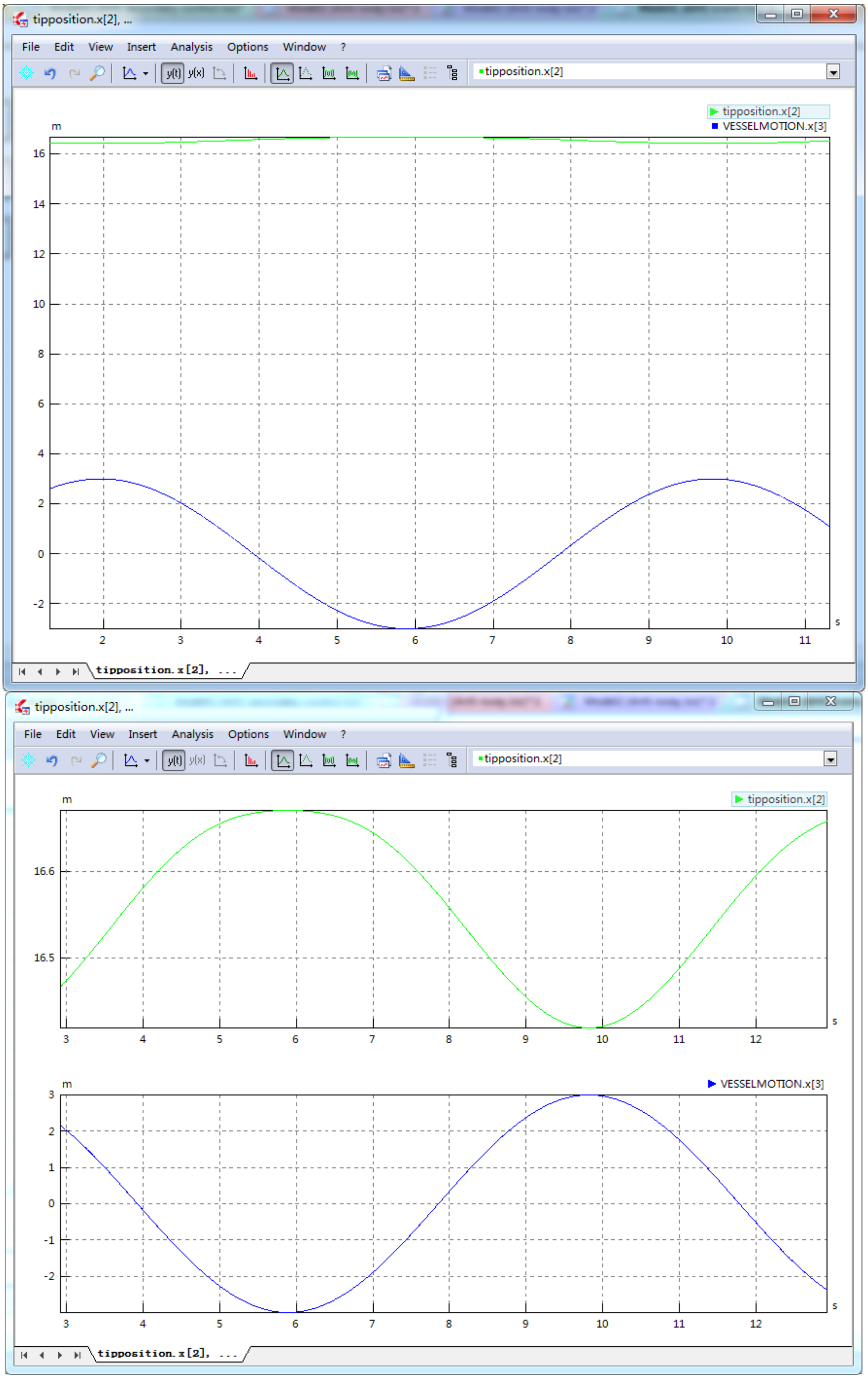


Figure 4.3.3 the displacement of the ship and crane tip

The X-axis is the time and the Y-axis is the displacement in meters. The green line is the displacement of the crane tip and the blue line is the displacement of the vessel motion. From the plots we can see the motion of the crane tip is very small compare to the vessel.

5 ANTI-SWAY CONTROL AND SIMULATION

During the real operation of offshore crane, the load sway is also exists. In this chapter we will introduce how to reduce the sway of the crane payload. To reduce the kinematic and potential energy of the load. The method is to make the crane tip move to the load sway direction. Another method is to control the winch. When the payload moves toward to the crane tip increase the wire length. When the payload moves away from the crane tip shorten the wire length.

In this report the anti-sway control is only can fix the 1DOF sway of the payload.

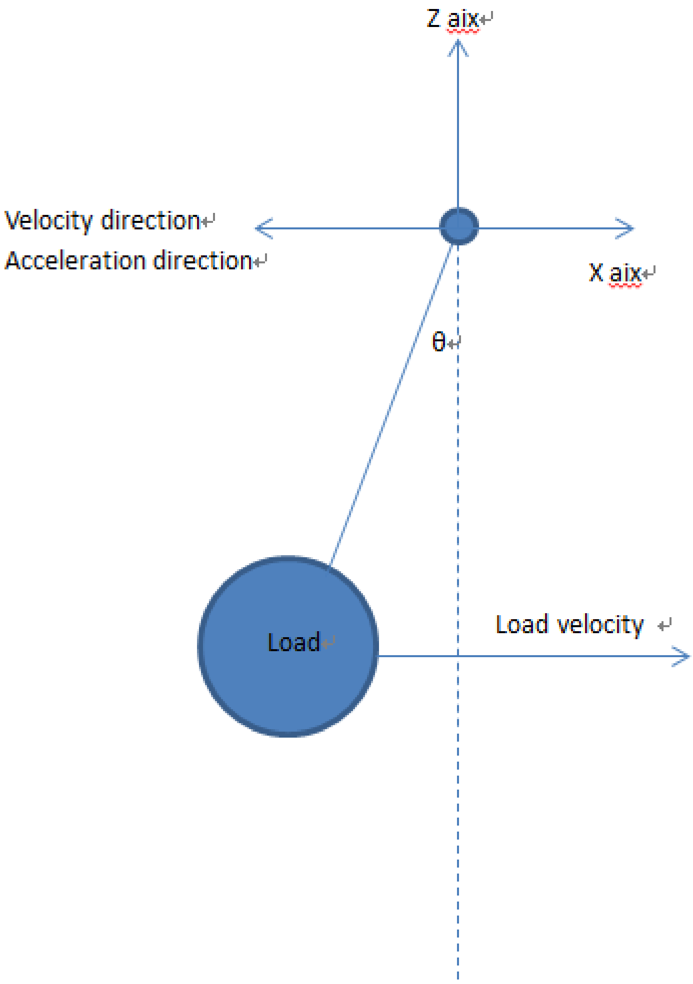


Figure 5.1.1 1DOF pendulum

The figure shows the load sway during crane operation. The crane tip starts move to the load sway position. When the distance between the crane tip and load is smaller than a certain value. It should stop to move. The aim is to prevent the overshooting. The crane tip starts to accelerating to the opposite direction when the distance between the load and tip is close.

The distance is calculated by:

$$\Delta x = \left|\frac{1}{2}V_{crane\ tip} - V_{load}\right| * \Delta t$$

Where $\Delta t = \frac{V_{crane\ tip}}{a_{max}}$ *is the time it takes to reduce the tip velocity to zero. The* a_{max} *is the max acceleration of the crane tip. Because the distance between the load and the crane tip is very small. So in the formula above the acceleration is neglected.*

Modelling and simulaiton in simulationX

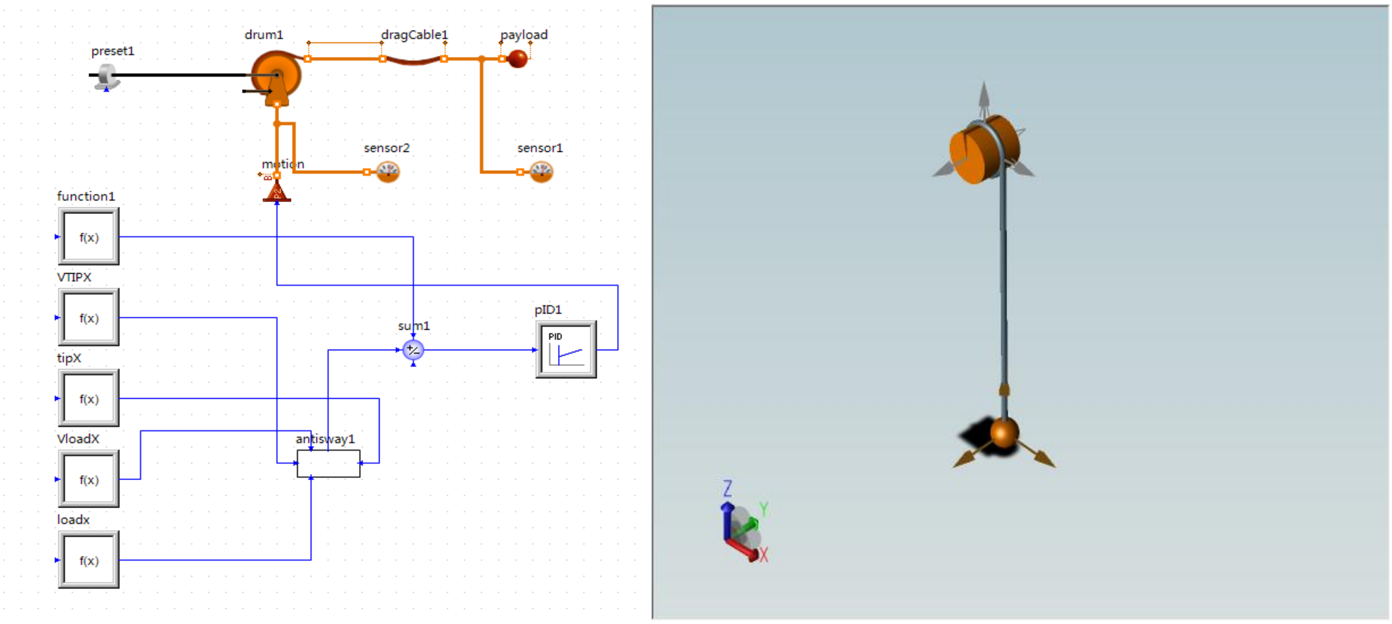


Figure 5.1.2 The simplified model of pendulum in simulationX

The figure shows the model and hydraulic system of the antisway control. I use a drum connected to a payload to simulate the system. The function 1 send the acceleration from the sensor2 in the drum. The sensor1 is use to collect the velocity, displacement, acceleration of the payload. Then send these signals to the antisway control system.

In this thesis work , I mainly focus on the system bulit and modelling. So the control system test will put in the further. But I will put the program code in the appendix.

6 DISCUSSION

Original model and system dimensions select is important for the simulation and system analysis.

I use UG NX8.5 to bulit the offshore crane model. From the simulation result we can get a lot of experiences about modelling and simulaiton work after the thesis work. In my project we can find that some values of my plots like the torque and pressure of the hydraulic system are too big. It is hard to find system fluctuate if the variables are very big in the simualtion plots. However the aims of simulaiton are helping us to find the system problems and fix the design imperfection or even errors. So when we bulit the model for simulation and analysis we should choose typical cases built with standard components. Ensure the dimensions of your system will easy to analysis and simuale before you start your work.

The problems I meet when use the typedesigner of simulationX

Typedesigner in the simulationX is use to built new components which are not included in the library. The program code in simulationX is called modelica.[9] The system program is my weak side becasue i am not familiar with this area. I encounter a problem when i did the active heaven compensation of the kinematic control. The system could not define a matrix freely and the syntax is also error. I try to find a introduce PDF of the program code and i finally fix the problems from the help file in another similar software. The best place you type in your program code In the typedesigner of simulationX which you should program a system is not the behavior label but the modelica code label.

The jacobian matrix in the control system of this part is calculated by the matlab. Because there is a problem of matrix define in the simualtionX. So i skip this part and directly use the numerical matrix in the calculate of the jacobian to control the active heaven compensation system. And from the simulation we can see the effections of the results. This part is need to be improved in the further work.

SmulaitonX and 20sim

Since i have studied and done some projects which are similar to this thesis work in 20sim. I will talk about the characteristics of these two simulation softwares.

20sim is based on the bond graph principle.[10] In the simulaitonX we use the modelica code to program the new components or just use the components library directly. The components library of the 20sim is mainly include signal processing and bond graph junctions. All the real components should bulit by yourself and the system should be simplified first. The system structure figure of 20sim is hard to understand and display to the other people. In other word it is not intuitive enough compare to the simulationX.

Consider to the program code of these two softwares. The code syntax of 20sim is easier. If you need to bulit a new system and almost all the components are make by yourself, the 20sim is a better choice compared to the simulationX. The program code is easy to write and then you can simplified the system as you wish.

The advantage of use simulationX is its big and comprehensive components libray. Although use the components library in the simulaitonX can bulit a complete system easily and fast, there also will be a lot of problems. Becasue there are too many parameters need to be defined. Some of them maybe have nothing to do with your system. However this also means the simulationX is more perfossional. If you are familiar with the system you bulit and understand every parameters of the components, the simulaitoX is a better choice. The help documents in the simulationX which introduce how they built the components and the working principle are very helpful.

I also study some previous wrok about the offshore crane and its hydraulic system simulation based on 20sim. In the crane control simulation with active heaven compensation we can not see the hydraulic system response when handling heave compensation. This part is also a same problem in my project. But in my project i have inroduce a model to fix this case.

For my thesis work the biggest problem in the simualtionX is the control signal sources. Because there is no joystick junction in this software. So in my thesis wrok all the control signal sources use the slider control bar to achieve. I think this will also effect the simulaiton results and should be fixed.

<u>The extra work and mistakes</u>

The secondary winch control of the active heaven compensation is temporarily added in my thesis work. So i just introduced the priciple and finished the modelling part. The relationship between the motor displacement and the rotation speed still need to be solved. The rationality of the system dimentions should be tested also.

The anti-sway system was modelled and tested with the winch hydarulic system. The result in the anti-sway part is quite different from the expection. I think the first reason is i use a drum to connect the payload to do the simulaiton. The drum has diameter and the initial wire rotate on the drum will also affect the system working, make it hard to judge the displacement from the payload to the connect point. The second reason is i use the acceleration as the control signal to control the system. The velocity control will be more directly. The third reason is not totally understand the energy disspating priciple. In my simulation result when the dx(the distance when the tip has to starts its accerleration into the new direction) is equal to the deltax (the absoulate value of the distance between the crane tip and the payload) the simulation will become very slow even stopped. The program code of this part still need to re-reflection.

To sum up , in this thesis wrok i study the simulation and modelling method of the offshore hydraulic crane system. And the basic principle of AHC and anti-sway control system. Learned a new program language modelica. And the integration of 3D model and its sub control system simulation. Simulation results analysis and complete system design based on the results.

7 CONLCUSIONS

This thesis wrok is mainly focused on the modelling and simualtion project. The motivation is to improve the working situation of offshore crane in the deck and provide a simulation model for crane design or study.

In this project an offshore crane model was bulit including its hydraulic system models (the slew ring, winch , and cylinder). In the simulation part the active heaven compensation and antisway model were built based on the simulaitonX. We can study the performance of the hydraulic system during crane operation through simulation the system.

After that we discuss the results. Through the simulation of the model we can study the working situation and test some new control system based on our project work. For instance, in the AHC part we also bulit a new system which is more useful in the real life. I think in this thesis report the two most important parts are the system modelling part and the AHC modelling part. In the crane system modelling part we can see the characteristics of simulationX clearly. In the AHC modelling part we also can study the crane control and hydraulic systme working performance very clearly.

The control methods of these two systems were also provided. In the active heaven compensation the normal winch control and the kinematic control were finished and the working performances were showed through the plots.

Based on my thesis work we can extend the compensation system to the rolling compensation or other areas. Try to integrate all the control system in one crane and do the simulation to research if there are any differences between the single system opertion results.

8 FURTHER WORK

Finish active heaven compensation of the secondary winch control

The model was finished so the further work is to find the relationship between the motor displacement and the rotation speed.

Fix the problems of anti-sway control in the simuationX and extend the control from 1 DOF to 2 DOF

The problems of this part were analysis in the conclusion and discussion part. Based on the energy dissipating principle to bulit the program. And change the acceleration control to velocity control will helpful.

Integration all the hydraulic compensation system to the crane model

Single system simulaiton and integration system simulation is quite different. Compare the results and fix the interactions of them. Analysis the response of each hydraulic system.

Try to make the hydraulic components with the typedsigner in the simualtionX

The components library in simulationX is comprehensive. However the defects of the components is consider too many parameters. Some of them will effect the simulaiton. So try to bulit a more simplified components library to make the simulaiton results more reliable.

Some advise about using the simulationX

Before start the mdelling and simulation read the tutorials on the simulationX web.

Study the help document of the components in your system before you integrate them together. Test the components one by one before you connent them together.

When the simulation becomes very slow try to adjust the calculate step.

Study the example system in the software, try to imitate.

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10 APPENDIX

10.1 Appendix A

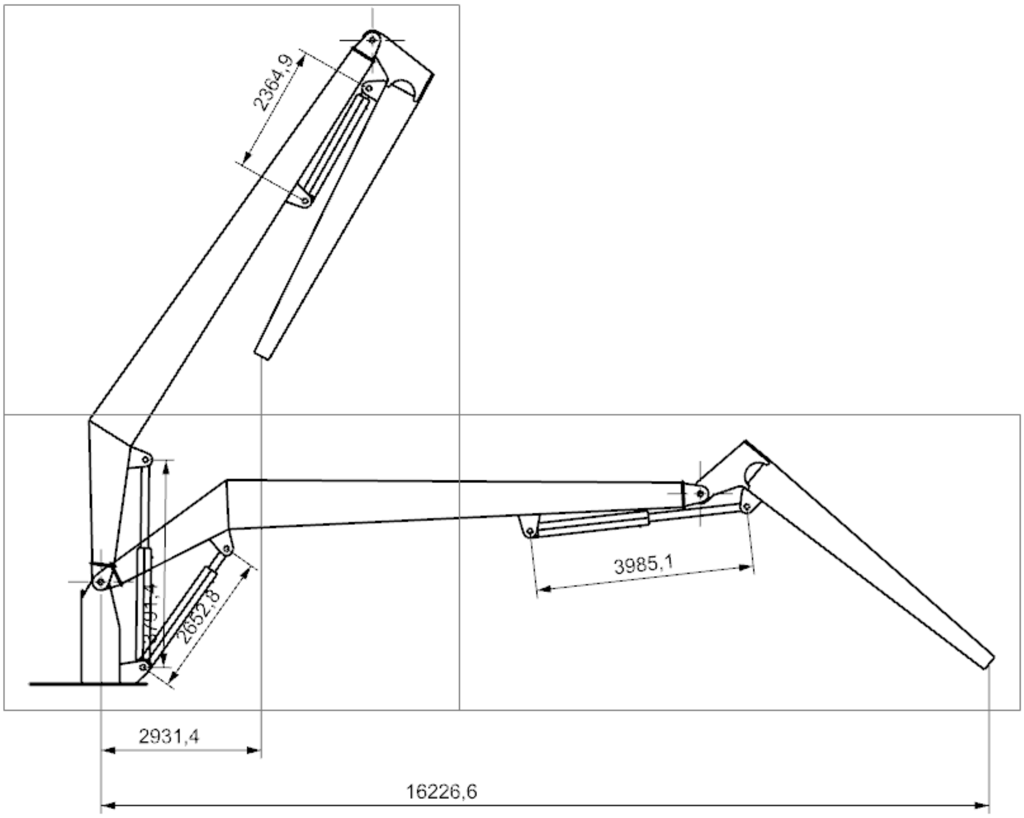

Figure 10.1.1 The rough dimensions of crane model

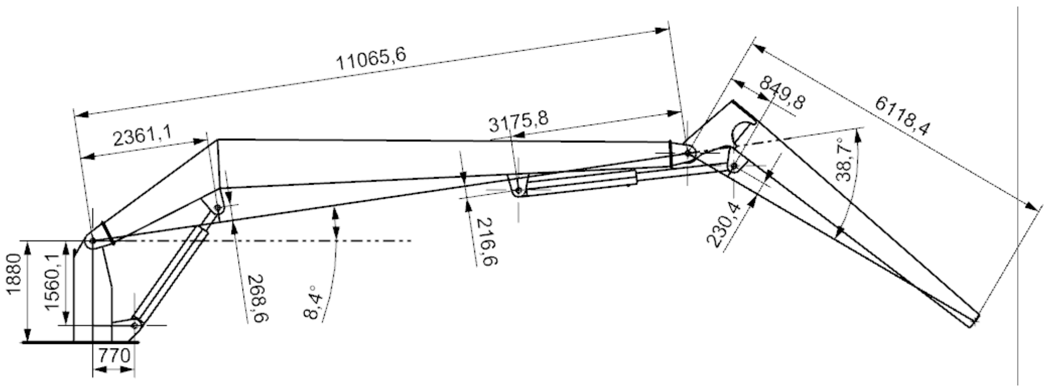

Figure 10.1.2 Rough dimensions of the main structure

10.2 Appendix B

Program code of compensator in typedesigner

```
// Flow
mdot = portA.mdot;
portB.mdot = -mdot;
portLS.mdot = 0;
Q = mdot/(0.5*portA.rho + 0.5*portB.rho);

// Pressures
pA = portA.p;
pLS = portLS.p;

if p0 <= pA - pLS then
pB = pLS + p0;
elseif pA - pLS > 0 and pA - pLS < p0 then
pB = pA - pLS;
else
pB = pLS;
end if;

portB.p = pB;
```

Program code of AHC jacobian control components

```
model JACOBIAN "jacobian"
    input SignalBlocks.InputPin tippositionX[*] "Signal Input";
    output SignalBlocks.OutputPin rotationspeed1[*] "Signal Output";
    output SignalBlocks.OutputPin rotationspeed2[*] "Signal Output";
    output SignalBlocks.OutputPin rotationspeed3[*] "Signal Output";
    input SignalBlocks.InputPin tippositionY[*] "Signal Input";
    input SignalBlocks.InputPin tippositionZ[*] "Signal Input";
    Real jointV1(
        quantity="Mechanics.Rotation.RotVelocity",
        displayUnit="rad/s") "Variable";
    Real jointV2(
        quantity="Mechanics.Rotation.RotVelocity",
        displayUnit="rad/s") "Variable";
    Real jointV3(
        quantity="Mechanics.Rotation.RotVelocity",
        displayUnit="rad/s") "Variable";
    Real M[3]={tippositionX,tippositionY,tippositionZ};
    Real N[3,3]={{0,0.0000616,0},{-0.0001248,0,0.0000729},{0.0003834,0,-0.0000347}};
    Real B[3]=M*N;
    equation
        // enter your equations here
        jointV1 = rotationspeed1;
        jointV2 = rotationspeed2;
        jointV3 = rotationspeed3;
        rotationspeed1 = B[1];
        rotationspeed2 = B[2];
        rotationspeed3 = B[3];
    annotation(...);
end JACOBIAN;
```

The program code of anti-sway control components

```
// enter your equations here
Vmax = 3.2;
Amax = 4.5;
dt = abs(VtipX)/Amax;
dx = abs(VtipX/2-VloadX)*dt;
deltaX = abs(tipX-loadX);
ctr1 = VtipX;
ctr2 = tipX;
ctr3 = VloadX;
ctr4 = loadX;
if deltaX > 0.5 then
if tipX > loadX then
 if deltaX > dx then
  if abs(VtipX) < Vmax then aTIPx = -Amax;
  else
  aTIPx = 0;
  end if;
 else aTIPx = Amax;
 end if;
elseif tipX < loadX then
 if deltaX > dx then
  if abs(VtipX) < Vmax then aTIPx = Amax;
  else aTIPx = 0;
  end if;
 else aTIPx = -Amax;
 end if;
else aTIPx = 0;
end if;
else ctr5 = 0;
end if;
ctr5 = aTIPx+friction;
```

10.3 Appendix C

The torques of joints generated by the payload could be calculated by the equation below:

$$\tau = J^T \cdot F$$

Where

τ is the vector of joints' torques

J^T is the Jacobian matrix

F is the static force acting on the tip

Thus the static joint torques generated by the payload are expressed by the following equation

$$\tau_{payload} = \begin{bmatrix} -L_3 s1c23 - L_2 s1c2 & L_3 c1c23 + L_2 c1c2 & 0 \\ -L_3 c1s23 - L_2 c1s2 & -L_3 s1s23 - L_2 s1s2 & L_2 c2 + L_3 c23 \\ -L_3 c1s23 & -L_3 s1s23 & L_3 c23 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix}$$

Similarly, the total torques on joint is the sum of torques generated by the payload and the weight of crane components. It could be expressed as:

$$\tau_{total} = \tau_{payload} + \tau_{crane}$$

Static forces on cylinders

The calculation of cylinder forces is based on the equation of moment balance. First of all, establish a geometric model of one joint and cylinder to figure out the relationship between them.

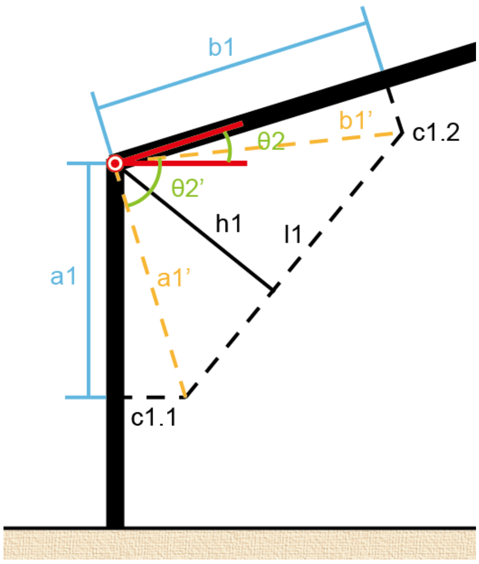

Figure 10.3.1 Geometric model of one joint and cylinder

In the figure above, l1 is the length of cylinder and h1 is the distance from joint to cylinder.

The moment equation is known as:

$$\tau = h * F$$

Thus, the distance from joint to cylinder is required to get for calculating the cylinder force.

For the first joint (base-boom)

$$h_1 = \frac{a_1' b_1' \sin(\theta_2')}{l_1} \qquad 10\text{-}1$$

$$a_1' = \sqrt{{a_1}^2 + {c_{1.1}}^2} \qquad 10\text{-}2$$

$$b_1' = \sqrt{{b_1}^2 + {c_{1.2}}^2} \qquad 10\text{-}3$$

$$\theta_2' = \theta_2 + \frac{\pi}{2} - \arctan\frac{c_{1.1}}{a_1} - \arctan\frac{c_{1.2}}{b_1} \qquad 10\text{-}4$$

$$l_1 = \sqrt{{a_1}^2 + {b_1}^2 - 2a_1b_1\cos\left(\theta_2 + \frac{\pi}{2} - \arctan\frac{c_{1.1}}{a_1} + \arctan\frac{c_{1.2}}{b_1}\right)} \ 10\text{-}5$$

Substitute the equations (2-2) (2-3) (2-4) (2-5) into equation (2-1):

$$h_1 = \frac{\cos(\theta_2 - \arctan\left(\frac{c_{1.1}}{a_1}\right) - \arctan(\frac{c_{1.2}}{b_1}))\sqrt{({a_1}^2 + {c_{1.1}}^2)({b_1}^2 + {c_{1.2}}^2)}}{\sqrt{{a_1}^2 + {c_{1.1}}^2 + {b_1}^2 + {c_{1.2}}^2 + 2\sin(\theta_2 - \arctan\frac{c_{1.1}}{a_1} + \arctan\frac{c_{1.2}}{b_1})\sqrt{({a_1}^2 + {c_{1.1}}^2)({b_1}^2 + {c_{1.2}}^2)}}}$$

Similarly for the second joint (boom-jib)

$$h_2 = \frac{-\sin(\theta_3 - \arctan\left(\frac{c_{2.1}}{a_2}\right) - \arctan(\frac{c_{2.2}}{b_2}))\sqrt{({a_2}^2 + {c_{2.1}}^2)({b_2}^2 + {c_{2.2}}^2)}}{\sqrt{{a_2}^2 + {c_{2.1}}^2 + {b_2}^2 + {c_{2.2}}^2 + 2\sin(\theta_3 - \arctan\frac{c_{2.1}}{a_2} + \arctan\frac{c_{2.2}}{b_2})\sqrt{({a_2}^2 + {c_{2.1}}^2)({b_2}^2 + {c_{2.2}}^2)}}}$$

Thus the cylinder forces F1 and F2 could be calculated with the equation:

$$\begin{bmatrix} \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} h_1 & 0 \\ 0 & h_2 \end{bmatrix} * \begin{bmatrix} F_{cyl1} \\ F_{cyl2} \end{bmatrix}$$

Where

τ is the torque of joint

h is the distance from joint to cylinder

F is the cylinder force

Total force at base-boom joint

$$\vec{F}_{BB} = \vec{F}_{cyl1} + \vec{F}_{SWL} = \sqrt{\left(\sin\theta * F_{cyl1}\right)^2 + \left(\cos\theta * F_{cyl1} - SWL\right)^2} = 1169KN$$

Total force at boom-jib joint

$$\vec{F}_{BJ} = \vec{F}_{cyl2} + \vec{F}_{SWL} = 1391KN$$