MODELLING AND SIMULATION OF AN OFFSHORE HYDRAULIC CRANE

Yingguang Chu, Vilmar Æsøy and Houxiang Zhang
Department of Maritime Technology and Operations
Aalesund University College
PO Box 1517, N-6025 Ålesund, Norway
Email: yich@hials.no
ve@hials.no
hozh@hials.no

Øyvind Bunes
Deck Machinery Seismic & Subsea
Rolls-Royce Marine
PO Box 193, N-6069 Hareid, Norway
Email: Oyvind.Bunes@Rolls-Royce.com

KEYWORDS
Bond Graph, offshore crane, hydraulic system, modeling and simulation

ABSTRACT

This paper presents a modeling approach based on Bond Graph (BG) method for offshore hydraulic crane focusing on its hydraulic system characteristics. A hydraulic library is built in the modeling software tool 20-sim using BG elements. The hydraulic submodels are designed according to one specific type of offshore crane, however, they can be easily modified and reused for other similar systems. BG method is a modelling technique for modeling of complex system by describing the energy flow inside the physical system. One of the main benefits of modeling using BG for the hydraulic system is the model provide interfaces to systems of other domains, for example, cooling system, mechanical model, control unit, etc. In this paper it is shown how an integrated BG model of the hydraulic system for a knuckle boom crane is derived and used for simulation. The simulation results proved the validation and effectiveness of the presented modeling approach for simulation of multi-domain systems.

INTRODUCTION

Cranes are found onboard almost all kinds of vessels and platforms for handling personnel and cargo. Cranes onboard vessels and platforms handling goods between the quayside and vessel or between vessels are normally referred to as offshore cranes. Cranes that are used for handling submerged loads as well e.g. launch and recovery of submersibles or installation of subsea hardware, are normally referred to as subsea cranes. Compare to land based cranes with a solid fixed base, offshore and subsea cranes are subject to significant dynamic forces from the resulting payload sway directly or indirectly caused by the vessel motion. As field testing in offshore industry is expensive and time consuming to carry out and constrained by many factors such as weather condition and vessel availability, modeling and simulation become a crucial part for product design, testing and analysis.

On one hand, offshore cranes are mostly hydraulic actuated due to the consideration for stable performance and safety redundancy. On the other hand, it is rather delicate to model and control hydraulic systems because of the complex dynamic behavior and nonlinear aspect of fluid energy transfer. Many studies on hydraulic system modeling dedicated to one or several specific components. There are many software tools available for modelling and simulation of hydraulic systems. Modelling tools used in former researches include SimHydraulic from MathWorks (Věchet and Krejsa 2009), Easy5 from MSC (Li et al. 2011), SimulationX from ITI (En et al. 2013), 20-sim from Controllab (Aridhi et al. 2013), etc. These programs provide standard libraries for hydraulic components which can be parameterized and modified to certain levels.

The generalized models are not designed for a specific system which means they might be over-complicated thus compromise the simulation efficiency. It is possible, to a certain level, to create new specific models for components that are not included in these libraries from these software tools, but that's not always the best way. Take 20-sim as example, a hydraulic library is developed according to the Modelica hydraulic library. The library doesn't include all the valves in a crane system. Instead of using BG elements, the models are written in a way which is difficult for the users to understand and edit. In this paper we present a modeling approach for offshore hydraulic crane system based on BG method. The submodels are created from scratch using basic BG elements and are completely open for editing as detailed as necessary depending on the simulation purpose. Another reason of choosing 20-sim as the modelling tool is using BG method complex systems, e.g. an offshore hydraulic crane, involving multiple energy domains can be modelled and integrated.

The rest of the paper starts with introducing the basics of the BG method and the hydraulic system of the kunckle boom crane. Then, the modelling of the main components using BG is described and the results from the simulation of the model are presented. Finally, the conclusion and future work is discussed.

BOND GRAPH METHOD

BG method as a general approach for modeling interacting systems is based on identifying the energetic structure in a system. A system can be decomposed into a few basic physical properties depending on what is going to be studied, and then the system can be described by interrelated idealized elements. The energy or power interaction between two elements is called a "power bond" represented by a half arrow. Another type of bond called "signal bond" represented by a full arrow indicates a signal flow at negligible power. A power bond is defined by two variables with generalized names of "effort" and "flow", of which the product is power. Table 1 lists a number of energy domains and their corresponding power variables.

Table 1 Common used BG energy domains

Energy Domain	Effort (e)		Flow (f)	
	Name	Unit	Name	Unit
Mechanical translation	Force	N	Linear velocity	m/s
Mechanical rotation	Torque	Nm	Angular velocity	rad/s
Electrical	Voltage	V	Current	A
Hydraulic	Pressure	Pa	Volume flow	m^3/s
Thermal	Temperature	K	Entropy flow	W/°C
Magnetic	Magneto-motive force	A	Flux rate	Wb/s
Chemical	Chemical potential	J/mol	Reaction rate	Mol/s

Roughly speaking, the basic elements account for energy supply based on supply of effort and flow (Se-element and Sf-element), potential and kinetic energy storage (C-element, I-element), energy dissipation (R-element) and energy transform (TF-element) or conversion (GY-element). In addition to the basic elements describing the boundary components, the interconnection in between two elements is described using an ideal 1-junction or 0-junction element, which neither store nor dissipate the energy. In brief, a 1-junction has equal flow on all bonds adjoining and the sum of efforts equals to zero, while a 0-junction is just the opposite: the effort is the same and the sum of flow is zero. The essence of defining an element is to establish the relation of the energy variables. Below Figure 1 so-called tetrahedron of state, illustrates the basic 1-port elements relating the energy variables (Pedersen and Engja 2008).

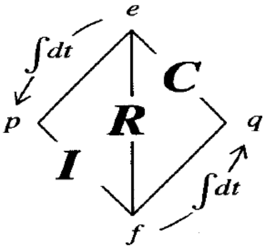

Figure 1: Tetrahedron of state for basic 1-port elements

OFFSHORE CRANE HYDRAULIC SYSTEM

The hydraulic system of a common offshore knuckle boom crane is studied in this paper. The crane consists of three joints actuated by a hydraulic motor and two hydraulic cylinders (Figure 2).

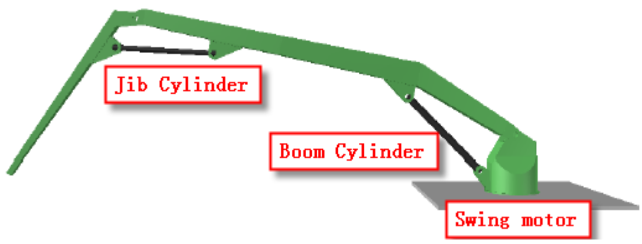

Figure 2: Offshore hydraulic knuckle boom crane

When considering the complexity of the model, it is vital that the simulation can be done in real time. Thus the hydraulic system schematic is simplified to include only the main components at a level corresponding to the characteristics that shall be studied (Figure 2). The main components of the crane hydraulic system include a Hydraulic Power Unit (HPU), pipelines, valves (compensator, 4/3proportional direction valve, load control valve), cylinders, and motors.

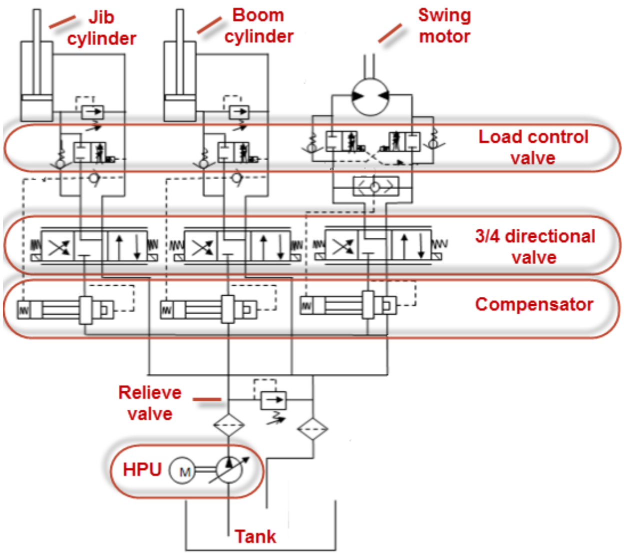

Figure 3: Hydraulic system schematic

BOND GRAPH MODELING OF CRANE HYDRAULIC SYSTEM

After identified the main components of the hydraulic system, in this chapter modeling of these components using BG elements is described. The hydraulic submodels are created based on the basic principles of fluid dynamics (ASSOFLUID 2007). To reduce the complexity of the overall model, the model of each component is also simplified. Fluid inertia and flexibility are dominant in the pipeline and cylinder chambers, thus neglected in the other components. As mentioned, BG method is modelling approach by describing the energy flow of the system. In the hydraulic domain, the key principle is to establish the connection of pressure and flow through the system.

HPU (pump)

The HPU of the crane mainly consist of a pressure compensated pump, which maintains a preset pressure at its outlet by adjusting its delivery flow in accordance with the pressure at any given time. If the system pressure is less than the pressure set point, the pump outputs its flow proportional to the pressure deviation. In the BG method a pump is modelled as a flow source element (Sf-element). The Sf-element has one output power port associated with the pump outlet. The effort and flow relationship is given by the following equations:

$$Q_{\max} = \frac{v}{2\pi}\omega \tag{1}$$

$$f = \frac{P_{set} - e}{\Delta P} Q_{\max} \tag{2}$$

Where v is the displacement of the pump, ω is the pump rotational speed, P_{set} is the pump pressure set point, ΔP pressure deviation from the set point that required giving full pump flow.

Pipe

The pipe submodel (Figure 4) describes segmental hydraulic pipelines with circular cross sections. The submodel accounts for friction loss along the pipe, fluid inertia and compressibility. The ControlVolume C-element is inserted in between pipe segments or other components as many as needed to avoid causality error and account for fluid flexibility in the areas that are not considered as pipes, i.e. with negligible inertia and frictional effects. The pipe sub-model has one input and one output power port associated with the physical inlet and outlet of the pipe segment.

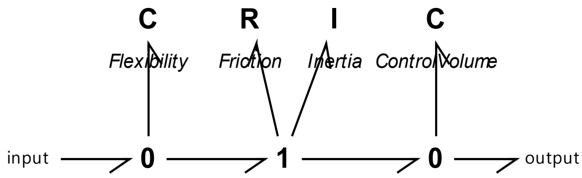

Figure 4: BG model of segmental hydraulic pipe

The Bond Graph elements are written by the following formulas:

Friction (R-element):

$$e = \frac{1}{2} k \frac{\rho l}{d} \upsilon^2 \tag{3}$$

Where the friction factor $k = \frac{64}{\text{Re}}$ for laminar flow given by the Darcy–Weisbach equation, and $k = \frac{0.316}{\text{Re}^{0.25}}$ for turbulence flow given by the Blausius equation. The Reynolds number is calculated by $\text{Re} = \frac{d}{A\upsilon} f$, ρ is the fluid density, υ is the fluid viscosity, d is the pipe diameter, l is the pipe length.

Inertia (I-element):

$$\int e dt = \frac{\rho l}{A} f \tag{4}$$

Where ρ is the fluid density, l is the pipe segment length, A is the section area of the pipe.

Compressibility (C-element):

$$e = \frac{B}{Al} \int f dt \tag{5}$$

Where B is the fluid bulk modulus, .A is the section area of the pipe, and l is the pipe segment length.

ControlVolume (C-element):

$$e = \frac{B}{V} \int f dt \tag{6}$$

Where B is the fluid bulk modulus, V is the volume of the fluid.

Valves

In the crane's hydraulic system, four types of valves are modeled; a relief valve, a compensator, a directional control valve and a load control valve. A valve submodel is described as a restriction nozzle which causes a pressure drop in the direction of flow. The relationship between the pressure and flow through the valve follows the general equation:

$$\dot{V} = c_d A \sqrt{\frac{2}{\rho} \Delta P} \tag{7}$$

Where $\dot{V}$ is the flow rate, c_d is the discharging coefficient, A is the valve orifice area, ρ is the fluid density and ΔP is the pressure drop across the valve.

Compensator (MR-element):
The compensator submodel represents a flow control valve which maintains a certain pressure differential over a hydraulic valve to minimize the influence of pressure variation on a flow rate passing through that valve. The compensator model has one input power port associated with the valve inlet, and two input signal ports associated with the pressure on both sides of the compensated valve. The valve opening area is proportional to pressure differential:

$$A = \frac{f_{dp}}{\sqrt{\frac{2dp}{\rho}}} \tag{8}$$

Where is f_{dp} the flow rate at a pressure drop of dp. The value can be read from the flow chart in the valve factsheet.

The flow rate is then calculated by:

$$f = \frac{P_{set} - \Delta P}{P_{set}} A \sqrt{\frac{2e}{\rho}} \tag{9}$$

Where P_{set} is the pressure set point over the compensated component, ΔP is the pressure differential over the compensated component, A is the valve open area. ρ is the fluid density.

4/3proportional direction valve (R-elements):
The 4/3proportional direction valve submodel (Figure 5) represents a continuous 3-way-4-port directional valve. The fluid from the compensator is distributed between two output ports A and B and return to the output port Tank, varied by the slide position.

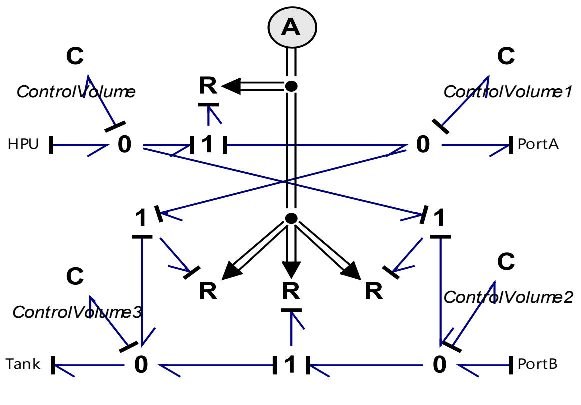

Figure 5: BG model of 4/3 proportional valve

The valve R-element is written based on the general equation:

$$f = A \sqrt{\frac{2e}{\rho}} \tag{9}$$

Where the opening area A is signaled by the valve slide position which is controlled via an external controller, for example a joystick or a keyboard.

Load control valve (MR-element):
The load control valve submodel consists of a pressure control valve and a check valve that can retard actuator's movement when with overrunning loads. The submodel has one input power port and one input signal port associated with the pressure signal at the load side. The valve flow rate is calculated based on Equation (9). The valve is signaled by the pressure at the load side. Flow is free in one direction while proportional to the load side pressure in the other direction.

Cylinder
The cylinder submodel (Figure 6) represents the hydraulic cylinder which converts hydraulic energy into mechanical energy in the form of translational motion. Hydraulic fluid pumped under pressure into one of the two cylinder chambers forces the piston to move and exert force on the cylinder rod. The cylinder can transfer force and motion in both directions. The cylinder submodel has one input power port and one output power port associated with the cylinder A and B port. The cylinder submodel has a second output power port associated with the cylinder output force.

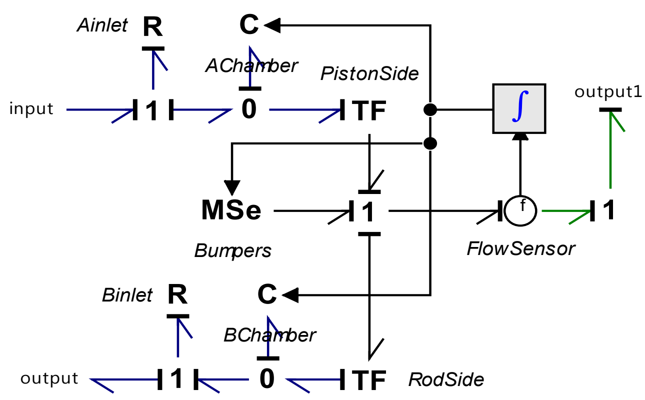

Figure 6: BG model of hydraulic cylinder

The cylinder inlets are modeled as restriction nozzles represented by R-elements. The relationship of power variables is given by Equation (9). The cylinder chambers are described as capacitors represented by C-elements. The power variables are given by Equation (6) where the volume is calculated by the cylinder piston position. The transformer elements (TF-element) transform energy between hydraulic and mechanical domain. The power variables are given by the following equations:

$$e_1 = \frac{e_2}{A} \quad (10)$$

$$f_2 = \frac{f_1}{A} \quad (11)$$

Where e_1 is pressure, e_2 is force, A is the fluid contact area to the cylinder, f_1 is the flow rate, f_2 is the cylinder speed.

The cylinder model also includes limitations presented by an MSe-element. The cylinder end positions, fully retracted and fully extended, are modeled as a spring-damper systems which allows a certain deflection. The effort and flow relationship is given by:

$$e = -k\Delta x - cf \quad (12)$$

Where k is the stiffness, Δx is the deflection of the bumpers and c is the damping factor of the bumpers.

Motor

The motor submodel (Figure 7) represents a fixed-displacement hydraulic motor which converts hydraulic energy to mechanical energy in the form of rotational motion. The motor can transfer torque and rotation in both directions. The submodel has one input power port and one output power port associated with the motor inlet and outlet. The submodel has a second output power port associated with the rotational shaft. As this is a high speed motor, a reduction gear is required to transform high speed and low torque to low speed and high torque.

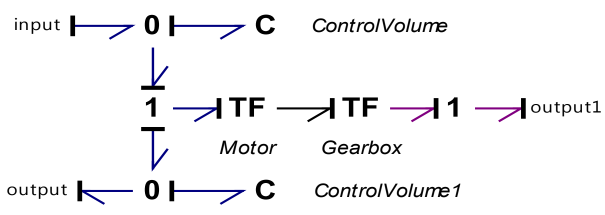

Figure 7: BG model of hydraulic motor and gearbox

The relationship of the power variables are given by the following formulas:

Motor (TF-element):

$$e_1 = \frac{\nu}{2\pi} e_2 \quad (13)$$

$$f_2 = \frac{\nu}{2\pi} f_1 \quad (14)$$

Where ν is the displacement of the motor, e_1 is hydraulic pressure at motor, e_2 is output torque of motor, f_1 is flow through motor, and f_2 is motor rotational speed.

Gearbox (TF-element):

$$e_1 = \frac{1}{n} e_2 \quad (15)$$

$$f_2 = \frac{1}{n} f_1 \quad (16)$$

Where n is gear ratio.

Tank

The Tank submodel is modeled as an open effort source (Se-element) with one atmosphere pressure, i.e. 100000Pa.

$$e = 100000 \quad (19)$$

With all the BG models built for the components, a complete circuit of the hydraulic system can be assembled. Figure 8 (Page 6) shows the BG model for the boom cylinder circuit of the crane. The input signal is sent to the directional valve for controlling the slide position for flow distribution.

SIMULATION RESULTS

Similarly, the hydraulic models for the jib cylinder and slewing motor circuit can be created. Due to the size limit of the paper they are not shown but grouped in the integrated model (Figure 9). In this model the crane is controlled via a joystick and the crane body is represented simply by some mass and inertia elements. A more explicit model of the crane body can be developed using BG as well and connected to the hydraulic model.

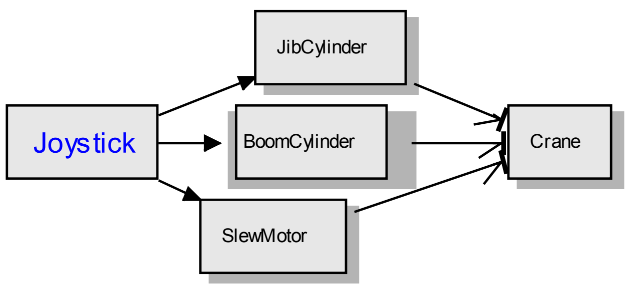

Figure 9: Integrated model of crane hydraulic system

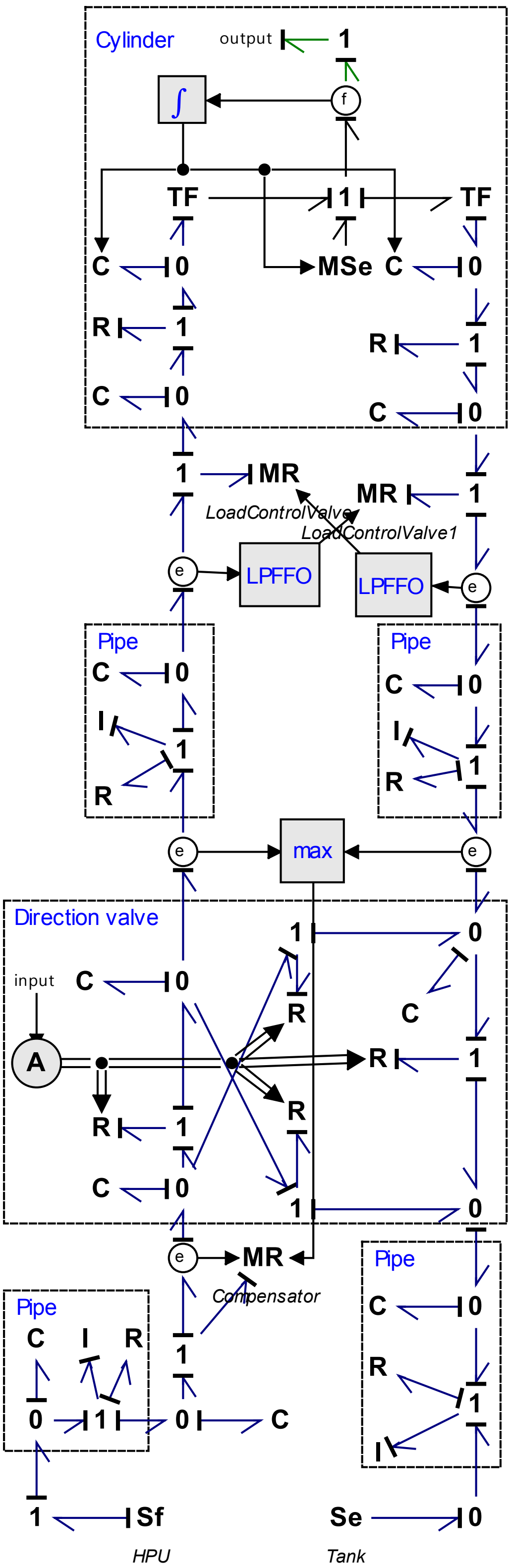

Figure 8: BG model of the crane boom cylinder circuit

All the variables in the model can be plotted during a real time simulation run. The following figures show the plotting of the boom cylinder circuit when the cylinder being extended and retracted. Figure 9 shows the boom cylinder position, which starts extending from its minimum position of 0.1m at 5s until fully extended to 0.9m at around 25s. Then the boom cylinder is retracted back from 25s till reaching its fully retracted position at 48s. Correspondingly, Figure 10 shows the pressures in the boom cylinder chambers. The pressure starts increase from 5s and when the cylinder is fully extended, the pressure at A chamber continues accumulating until reaching the maximum pressure, while the pressure at B chamber drop to zero. From 25s, when the cylinder is being retracted, the pressure increases in B chamber and decreases in A chamber until fully retracted at 48s. Figure 11 shows the flow distribution through the directional valve.

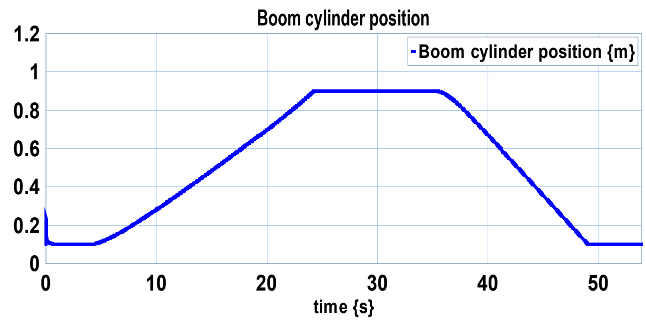

Figure 9: Boom cylinder position

The boom cylinder stroke is defined at 0.8m, with a minimum position at 0.1m to one end of the cylinder and 0.9m to the other.

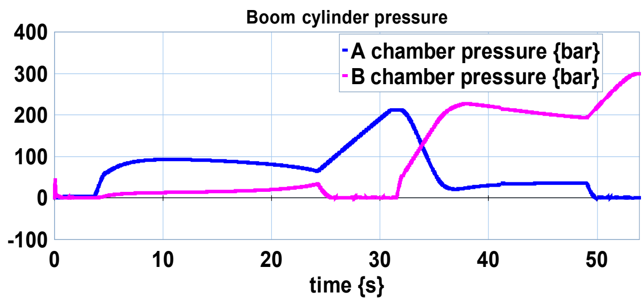

Figure 10: Boom cylinder pressures

The initial pressure at the cylinder is set at 1bar and the maximum limited pressure is 300bar.

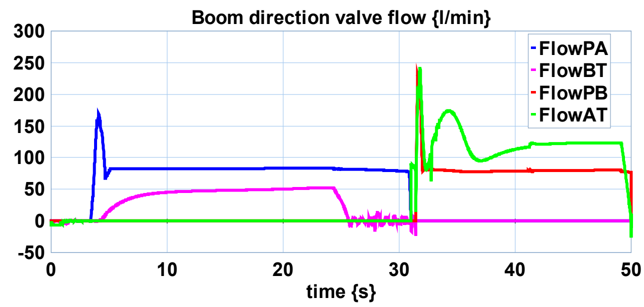

Figure 11: Flow through directional valve

The maximum flow through the proportional direction valve is 200 l/min limited by its opening area. The oscillations of the flow through the directional valve are due to the lack of damping in the cylinder when the end positions are reached.

As mentioned the model can be designed according to the simulation needs. The hydraulic characteristics can be plotted at any point inside the flow circuits. The running results for the slew motor and jib cylinder circuits are not presented due to the size limitation of the paper. It benefits for the crane designers and operators to dimension a crane and to monitor the performance of its hydraulic system.

CONCLUSION

In the previous chapters, a modeling approach using BG method for an offshore crane hydraulic system is described. BG method as a general modeling tool for physical systems allows for modeling of complex systems in multiple energy domains. The 20-sim software provides several modeling libraries and toolboxes for modeling systems of different energy domains. More important, it provides the flexibility to allow the users to build customized models and libraries. In fact, the models in 20-sim hydraulic library are not used because some specific components of the offshore crane system are not included, and the models are hard to understand or edit by the users. The presented hydraulic models of the crane system are built from scratch using basic BG elements.

As part of the future work, a more comprehensive hydraulic library will be developed for offshore machinery systems for modeling and simulation of hydraulic, mechanical, and thermal aspects. A dynamic model of the crane is another part of future work including a 3D animation scenery for visualization. It is also intended to include a hydro-dynamic ship model for study of the impacts of the waves to crane operations.

REFERENCES

ASSOFLUID, Italian Association of Manufacturing and Trading Companies in Fluid Power Equipment and Components. 2007. *Hydraulics in industrial and mobile applications.*

Aridhi, E; Abbes, M.; Mami A. 2013. “Pseudo bond graph model of a thermo-hydraulic system”. *2013 5th International Conference on Modeling, Simulation and Applied Optimization* (Apr. 28-30), ICMSAO, Hammamet, 1-5.

En Qiao Jiang, Shu Han Wang, Jing Ke Du, Xiang Yang Xu, Wen Yong Li . 2013. “Simulation of the Nozzle Electro-Hydraulic Servo Valve with ITI-SimulationX”. *Advanced Materials Research*, vol. 690-693, May 2013, 2912-2917.

Pedersen E.; Engja H.. 2008. *Mathematical Modeling and Simulation of Physical Systems.* Lecture notes in course TMR4257 Modeling, Simulation and Analysis of Dynamic Systems, Department of Marine Technology, Norwegian University of Science and Technology.

Věchet, S.; Krejsa, J. 2009. “Hydraulic arm modeling via Matlab Simhydraulics”. *Engineering Mechanics*, vol. 16, 2009, 287-296.

Yungang Li; Pengcheng Wang; Liqun Ai; Xiaoming Sang and Jinglong Bu. 2011. “Study on Hydraulic Circuit Simulation Based on MSC·EASY5 for the Arm of Excavator”. *Advanced Materials Research*, vol. 291-294, Jul. 2011, 2281-2286.

AUTHOR BIOGRAPHIES

Yingguang Chu studied Mechanial Engineering and Automation in Beijing Technology and Business University, China and obtained his bachelor degree in 2007. After three years working as a production engineer at Sonyericsson, China, he started a master study program in Hydraulic Engineering at Ocean University of China in 2010. After one year he moved to Ålesund, Norway, where he receieved his master degree in Product and System Design in 2013 and now continues as a research assistant and Ph. D. candidate at Aalesund University College.

Vilmar Æsøy received his Ph.D. in Mechanical Engineering in 1996 from Norwegian University of Science and Technology. From 1997 to 2002 he worked as researcher in Aker Maritime and R&D manager in Rolls-Royce Marine As. Since 2002 he works as Associate Professor at Aalesund University College.

Øyvind Bunes received his M.Sc. in Marine Technology from the Norwegian University of Science and Technology in 1996. Until 2002 he was employed as a researcher at MARINTEK until he joined ODIM, later Rolls-Royce, in 2002. He now serves as Senior Principal Engineer at Rolls-Royce Marine AS. He is also an Associate Fellow in the Rolls-Royce Engineering Fellowship and an Assistant Professor at Aalesund University College.

Houxiang Zhang received Ph.D. in Mechanical and Electric Engineering in 2003. From 2004 he worked as Postdoctoral Fellow at the Institute of Technical Aspects of Multimodal Systems (TAMS), Department of Informatics, Faculty of Mathematics, Informatics and Natural Sciences, University of Hamburg, Germany. Zhang joined the Department of Maritime Technology and Operation of Aalesund University College, Norway in 2011 and works as Professor on Robotics and Cybernetics.