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HYDRAULIC AND MULTIBODY COMBINED SIMULATIONS FOR ELECTRIC FORKLIFT DESIGN USING MODELICA

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ABSTRACT

As per modern day industry trends, most of the vehicles are getting converted into electric version from there conventional internal combustion engine version. This article focuses on electric Forklift conversion process by using the system simulation tool. The Electric version of the forklift also need to perform the similar variety of activities like conventional forklift does. Typical forklift is used to pick, transport and place the cargo at desired location. In the forklift, hydraulic power consumption is one of the major factor and that required pre-calculation of hydraulic forces, pressure and cylinder translation velocity characteristics before the electric conversion. Typically the one-dimensional system simulation are performed to predict the power consumption in hydraulic operation at early stage of the concept phase. In order to achieve this, the Modelica programming language is used to develop one-dimensional mathematical models in Dymola for virtual simulation of combined hydraulic and multibody dynamics operation. The developed model has ability to predict with reasonable accuracy of the different component performance like pump motor power consumption and also other system parameters viz. cylinder velocity. For multibody model, Modelica Standard Library is used. The developed model is used to calculate pump power required for a typical lifting cycle in forklift standard operation.

KEYWORDS: Modelica, Hydraulic, 1D simulations, forklift, Dymola, multibody dynamics

1. INTRODUCTION

The energy consumption from hydraulic operation is a key factor and major point to consider at electric version of forklift design. It is primary power consumer and also it should be considered as the main objective for battery pack sizing for electric forklifts. Hydraulic operation consume considerable amount of energy from Batteries, so at concept phase its energy requirement are pre-calculated by using commercial system simulation tool. During design process, the power consumption optimization with vehicle dynamic stability, there are some publications has been done using 1D system simulations approach [1]. Conventionally hydraulic system of a forklift has been designed in two phase viz., hydraulic system design separately and mechanical design separately. The latter mainly defines the maximum loading cycles and the structural integrity of the forklift and involves static and dynamic loading simulations. On the other hand, the hydraulic system design considers the maximum static mechanical loads for system sizing. Any modifications in mechanical design leads to modifications in the hydraulic system. This requires manual efforts to define force boundaries on cylinders in order to size hydraulic system components [2]. The key objective of this study is to establish an approach to consider aspects of mechanical design while designing hydraulic system using multi-physics simulations in Modelica language. It aims at providing methodology for hydraulic system simulations in Dymola.

2. FORKLIFT HYDRAULIC DESIGN

Design considerations

A forklift has a hydraulically operated mast mechanism for loading and unloading of goods and a mobile system for moving around. The mast mechanism is controlled by hydraulic actuators driven by hydraulic pump and controlled using various control valves. The forklift design considered is 4 wheel drive electric forklift with 2

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stage mast mechanism and 2T lifting capacity. Hydraulic pump is driven by electric motor. The design targets as shown in Table 1 were defined from technical specifications of already available forklift in the market [3].

Table 1 Design targets

Parameter	Value	Unit
Load capacity/rated load	2000	kg
Load center	500	mm
Tilt of mast/fork carriage forward/backward	5/9	deg
Height, mast lowered	2120	mm
Lift	3300	mm
Height, mast extended	3870	mm
Fork dimensions	35/120/1000	mm
Fork-carriage width	920	mm
Lift speed, with/without load	0.50/0.55	m/s
Lowering speed, with/without load	0.55/0.50	m/s

Forklift Mast Mechanism

Mast mechanism considered consists of 2 stage mast without free lift. As seen in Fig. 1, it has two main sections: outer mast and inner mast. Inner mast supports fork and carriage lifting whereas outer mast supports lifting of inner mast. Outer mast frame is hinged onto forklift body to allow tilting motion of complete mast assembly. Lifting carriage is connected to lifting cylinder via pulleys to achieve 2:1 mechanical advantage as seen in Fig. 2. This provides 2:1 ratio of lifting speeds of loads to cylinder piston extension. Thus overall hydraulic fluid flow demand is halved to achieve target lifting speeds [2]. The dimensions of the mast mechanism are derived from design target as shown in Fig. 1.

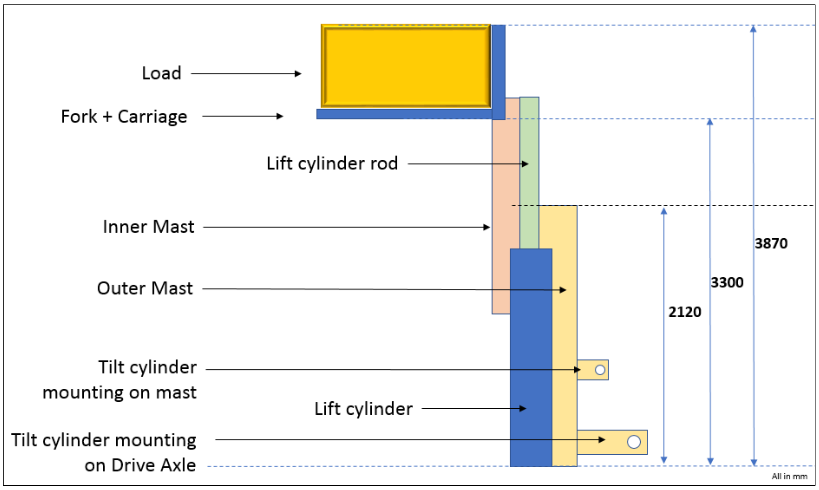

Fig. 1 Mast Mechanism

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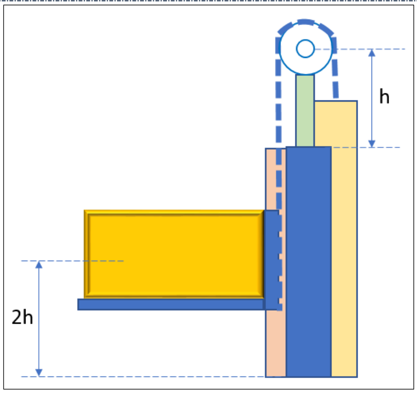

Fig. 2 Pulley Mechanism

Hydraulic System

Yu et al. [4] describes approach to select hydraulic components and define component sizing based on design targets in their paper. Similar approach is used to define hydraulic system components and its sizing. The hydraulic system has hydraulic actuators for lifting and tilting of the load. Lifting hydraulics includes 2 Ram type single acting lifting cylinders. Tilting hydraulics consists of 2 double acting cylinders fixed on forklift body and rod end connected to outer mast. Tilt cylinders can tilt the mast assembly from -9 ° to 5 ° with respect to vertical axis.

To drive the hydraulic system, a fixed displacement gear pump is selected based on design consideration. Pump is driven by an electric motor. Directional control valves control the flow in hydraulic cylinders thus controlling lifting and tilting operation. Also it included relief valve to safeguard hydraulic motor against overloading. Since lifting cylinders are single acting Ram type, the lowering is done with the help of gravity. Thus to ensure safe lowering speeds pressure compensated flow control valves are installed before cylinder delivery ports.

Flow control valves are also connected to tilt cylinder to control angular velocity of mast to safe level while tilting. The total hydraulic circuit taken into consideration is as shown in Fig. 3.

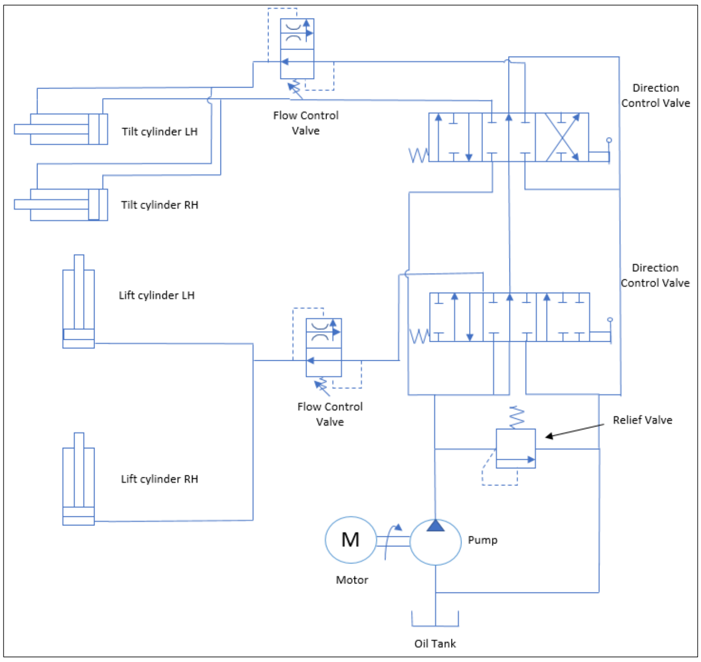

Fig. 3 Schematic of Hydraulic circuit

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The parameters of the hydraulic circuit used for simulations are as below.

Table 2. Parameters of the hydraulic circuit components

Parameter	Value	Unit
Pump		
Displacement	30	cc
Volumetric efficiency	90	%
Mechanical efficiency	85	%
Lift Cylinder		
Bore diameter	50	mm
Stroke length	1700	mm
Tilt Cylinder		
Bore diameter	100	mm
Rod diameter	40	mm
Stroke length	150	mm
Pump Motor		
Pump motor Speed	2200	RPM
Pump motor efficiency	80	%

3. SIMULATION MODEL DEVELOPMENT

Simulation Model Development

The 1D simulation model is developed using Dymola tool with Modelica libraries. Mast mechanism is modelled using Modelica Mechanics library. For hydraulic components, Modelica open source OpenHydraulics library [5] is used.

Mechanical body model

The mechanical linkage model developed using components from Modelica Mechanics library which is a part of Modelica Standard Library [6]. A multibody model prepared consists of simplified geometry for representations graphics but with actual geometrical data such as dimensions. As shown in Fig. 5, it consist of forklift vehicle chassis, tilt cylinders, mast assembly and lifting block which are identified with distinct colors. Lift cylinders are not shown in graphics for simplification. The multibody elements are connected with each other using library components such as fixed translation, revolute, translation, and body shapes modules. Load being lift is distributed on both fork arms equally and is represented with yellow boxes with mass of 1000 kg each. The interface of mechanical body with hydraulic network are mechanical flange port to be connected to mechanical flange ports of piston rod [6].

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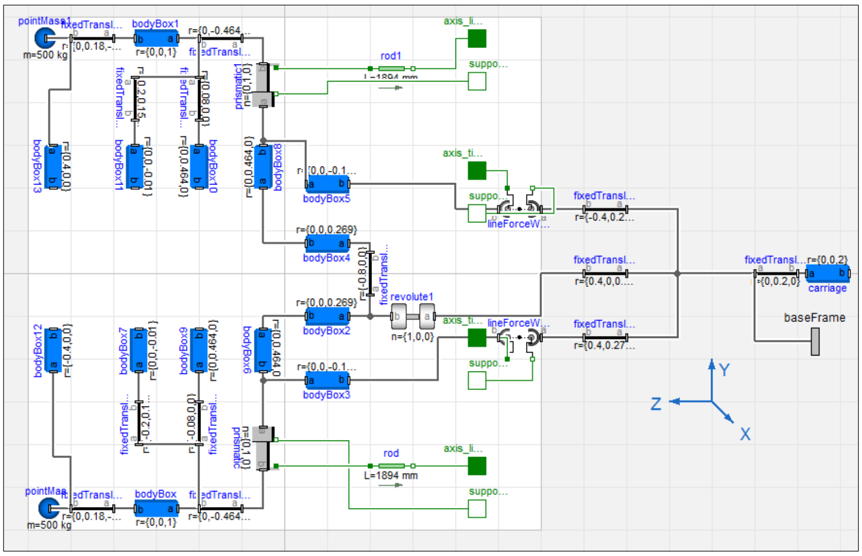

Fig. 4 Mast assembly - DYMOLA 1D model

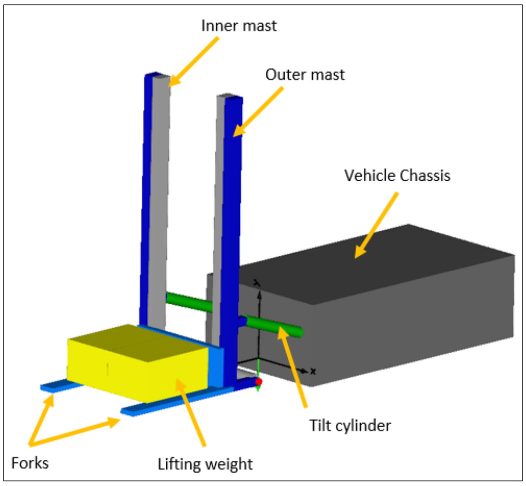

Fig. 5 Mast assembly - Dymola 3D Graphics

Hydraulic network model

The hydraulic network is modelled using components of Modelica OpenHydraulics library. The library components are capable of calculating transient simulations and also provide the interface to connect with other Modelica library components. A complete 1D simulation model is constructed by connecting mechanical flange interface ports to respective flange ports of pistons modules of hydraulic network as shown in Fig. 6

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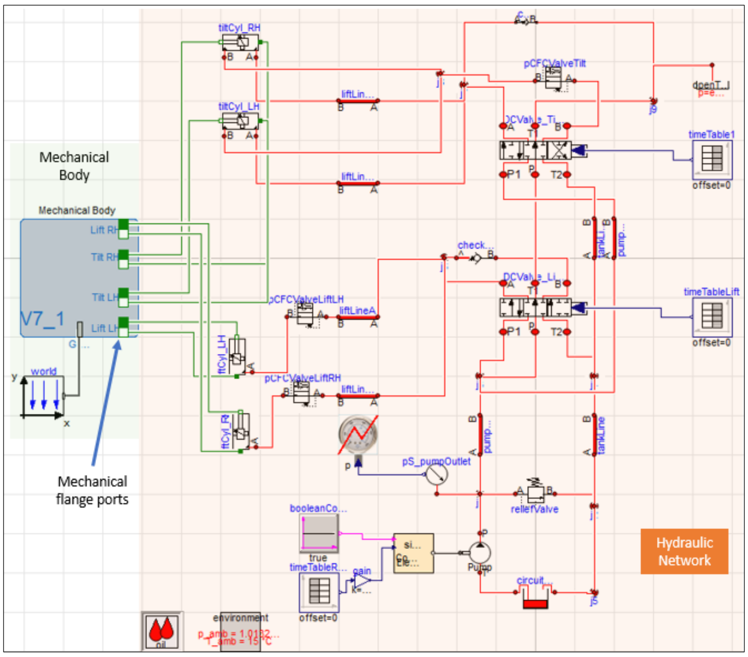

Fig. 6 Forklift – Dymola 1D model

4. RESULTS AND DISCUSSION

Power consumption analysis

The hydraulic power consumption of pump motor is calculated for one lifting cycle. Initially, lifting fork with load is placed in its lowest position. A delay of 4 sec considered to start the lifting, to avoid an influence of initial system vibrations on the lifting cycle output. After time t = 4 s, lifting takes place until load is raised to height of 2.5 m from ground then load will be lowered to initial position. Followed by a tilting backward by 9° and tilting forward by 9° to bring the mast in vertical position. The simulations are carried out for a total simulation time of 25 sec.

The design targets of lifting speed and tilting speed have been achieved successfully with above design. See Fig. 7 and Fig. 8 for results.

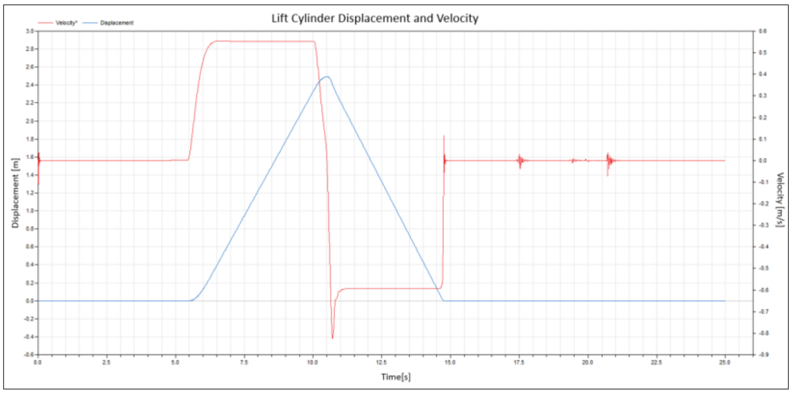

Fig. 7 Lifting Speed and Load displacement

Minor speed vibrations are seen at time t = 17.5 sec. This is due to the system undergoes abrupt inertia change which results in damped vibrations from the hydraulic system. Similar pattern is reflected at time t = 20 sec.

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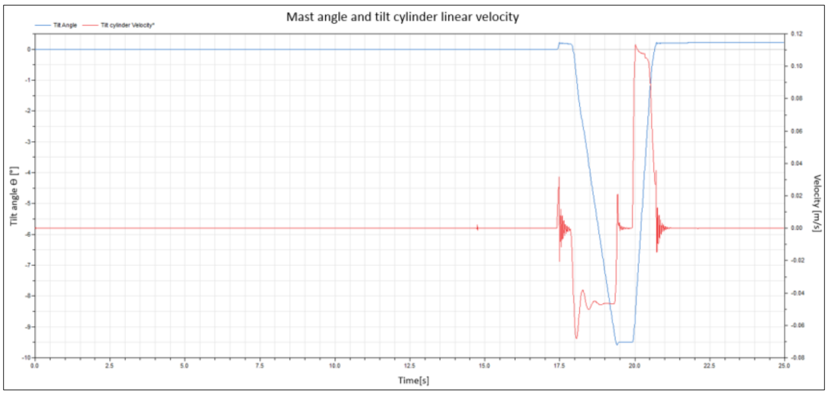

Fig. 8 Tilting speed and tilt angle

Pump outlet pressure for lifting predicted by model is 78 Bar.

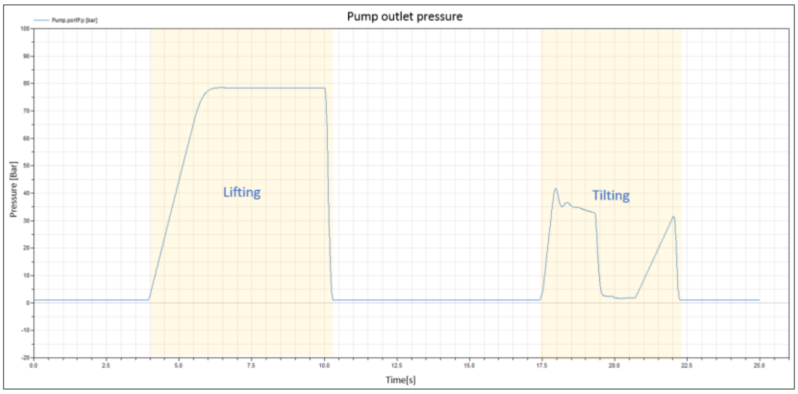

Fig. 9 Gear Pump outlet pressure

The hydraulic power consumption in one lifting cycle provides motor power required for design duty cycle. The Dymola model predicts pressure at pump outlet and thus torque required to drive the pump. This torque is provided by electric motor for which power can be calculated as shown in below equation.

Electrical power = Torque (N.m) x Speed (RPM) / 9.5488)/Electrical efficiency (i)

The power required from model is 11.7 kW which is also in line with published specifications [3] for the motor for the forklift considered herein.

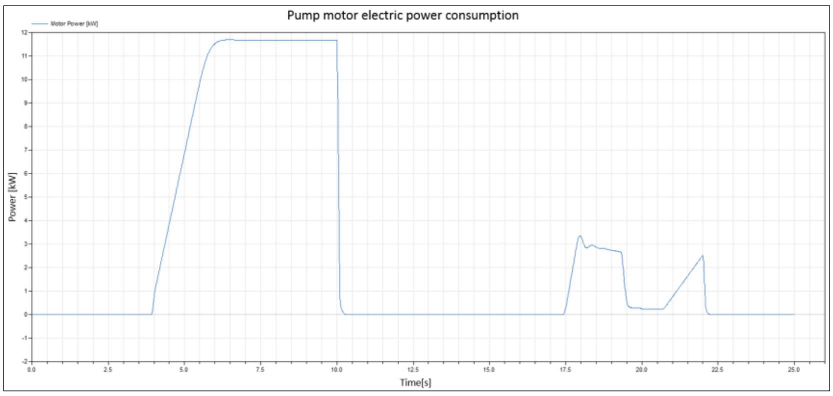

Fig. 10 Pump motor electrical power consumption

Design Iteration
With baseline model established, design iterations carried out to check the impact on system performance with change in lift load center from 500 mm to 750 mm. Model changes are carried out in mechanical module of mast assembly. No changes to hydraulic system modules required.

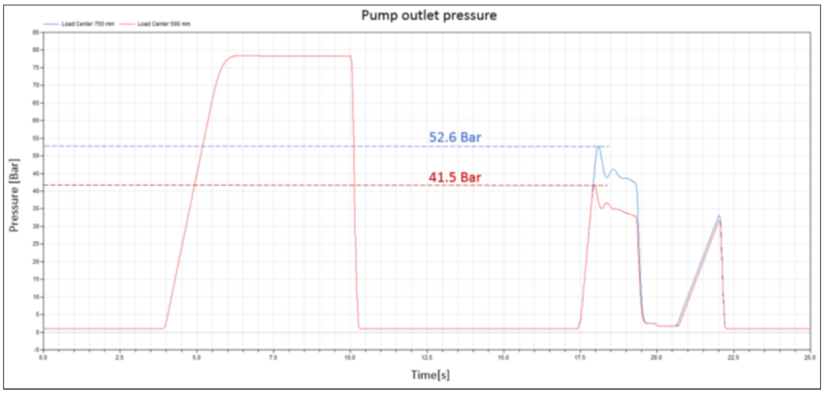

Fig. 11 Pump outlet pressure comparison for load center changes

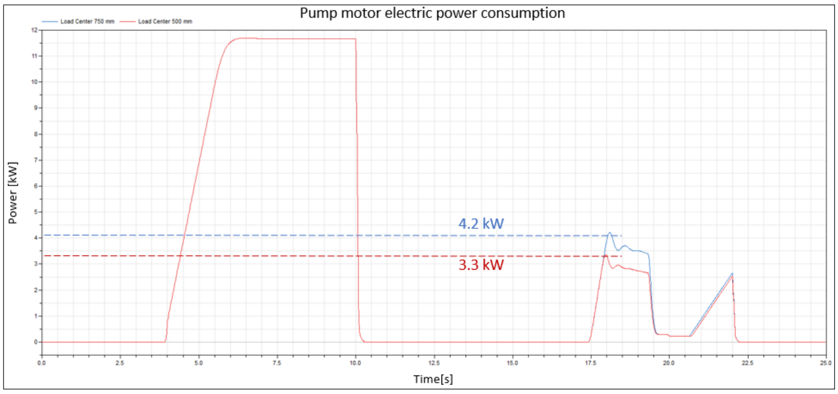

Fig. 12 Pump motor power comparison for load center changes

The result shows impact of tilting process on pump pressure. The change in load center has considerable impact on pump power consumption.

5. CONCLUSION

With the 1D modelling and simulations, the design criteria are checked and design iterations carried out to validate design changes. The validation has been performed by comparing the equipment performance data (cylinder velocities and power requirements) specified in the equipment manufacturer's catalogue. Multi-physics simulations allowed hydraulic system design to account for changes from the mechanical design with little additional efforts. Ability of integrated simulations allowed designers to quickly validate performance of the forklift lift design thereby reducing design cycle time.

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