Simulation of Tele-Operated Electro-Hydraulic Actuator and Excavator's Boom

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***Abstract*—This paper, we present our study called Tele-Operated Hydraulic Actuator which implying the usage of remote-controlled hydraulic system to control a mini excavator from a distance. Mini excavator comprises several motion mechanisms such as of swing, boom, arm and bucket. Simulation on the tele-operated electro-hydraulic actuator on boom mechanism has been conducted. The entire hydraulic system is modeled and simulate by using MATLAB software. The simulation result is discussed and described in order to analyze several system characteristics, given a certain working condition, within the simulation period**

***Index Terms*—Teleoperation; Mini Excavator; MATLAB@SimHydraulic.**

I. INTRODUCTION

There is no other tool has been more versatile than the excavator in the construction, mining, agriculture and wasted disposal fields works. However, the numbers of skilled operators are decreasing because it requires 3~5 years of operating experience to become skilled operator. Therefore, more research on excavator automation operations is being conducted in order to overcome this problem [1]–[3].

Tele-operated construction robot is a mobile hydraulic system which is controlled by the operator from a distance. The operator can perform dangerous tasks, such as removing debris and restoration work in extreme environments such as underwater, post disaster area and nuclear radiation area [4]–[8]. This teleoperation system has significant advantages which ensure the operator's safety by avoiding accident and injuries. Therefore, their development should be encouraged [9]-[10]. Tele-operated construction system consist of a master - slave system [11]. A 24V DC remote control is used as the master of the system while the Tele-operated Electro Hydraulic Actuator (T-EHA) which has been designed, acts as the slave of the hydraulic system.

The design of T-EHA utilizes the use of four-way electro-hydraulic spool valve due to some motion mechanism of the system; the stroke of the cylinder is required to be stopped at a certain condition according to the operator [12]. MATLAB and Simulink software consists of SimHydraulics software which is used for modelling environment for engineering design besides the simulation of a hydraulic control system. It refers to the Physical Network approach of the Simscape modeling environment [13].

II. METHODOLOGY

The simulation was conducted by using MATLAB software consisting SimHydraulic software under SimScape library. The Simscape libraries consist of basic hydraulic, electrical, mechanical, utility blocks, one dimensional translational and rotational mechanical elements.

A. *Tele-Operated Electro-Hydraulic Actuator System Model*

The model uses a 4/3 way directional control valve which has the maximum spool movement of 5mm. The directional control valve can be categorized as tandem-centred directional control valve. By referring to Figure 1, there are 4 hydraulic conserving ports which are P, T, A and B associated with the valve inlet, outlet, and actuator terminals respectively. The positive signal fed to the system opens orifices P-A and B-T, which allow the cylinder to extend. Negative signal open orifices P-B and A-T, which allow the cylinder to retract. The cylinder used has a full stroke length of 200mm, 2 hydraulic flow sensors and 2 hydraulic pressure sensors were placed at the cylinder inlet and outlet in order to determine the flow rate and pressure. In additional, an ideal translational motion sensor is placed at the cylinder stroke to indicate the length of the stroke.

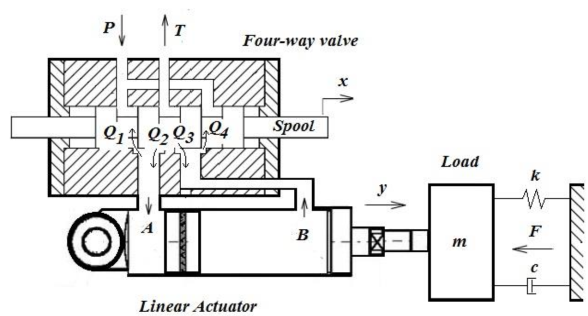

Figure 1: 4/3-Way Spool Valve

B. *Excavator's Boom Model*

Figure 2 shows a mini excavator parts and motion mechanisms. The model also utilizing 4/3 ways directional control valves due to its requiring position that need to be stopped at certain positions. The spool also has the maximum length of.5mm. The system also has almost the same components as the T-EHA system, but they differ in term of cylinder stroke length and initial cylinder position. The boom cylinder has the stroke of 500mm. The positive and negative signal fed allows the cylinder to extend and retracts respectively. There are also 2 hydraulic flow sensors and hydraulic pressure sensors mounted to the system at the inlet and outlet of the cylinder. The ideal translational motion sensor also was placed on the boom's cylinder in order to identify the stroke length of the cylinder.

C. Entire T-EHA and Excavator's Boom system

Figure 3 shows the entire T-EHA and excavator's boom modeling by using MATLAB software; Simulink, Simscape and SimHydraulic. The hydraulic system was pumped by using a fixed - displacement pump which was driven by mechanical motor. There is a pressure relief valve installed in the system to ensure that the pressure of the system not surpassed the specified pressure, 6 MPa.

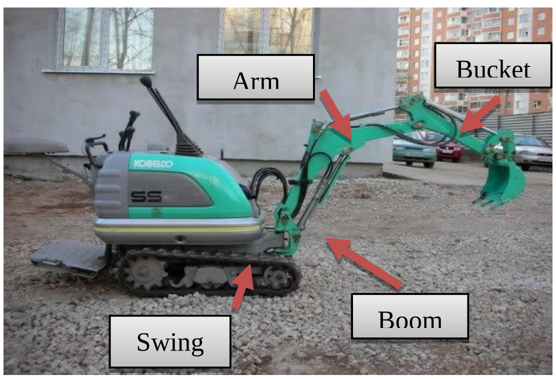

Figure 2: Mini Excavator

The motion of the spool for the T-EHA's directional control valve was driven by the given input signal. The initial T-EHA's cylinder position is in the middle of the stroke, which is 100mm stroke. This is because when positive signal fed to the T-EHA, it causes the spool to open orifice P-A, which allowing the cylinder to extend up to. On the other side, the spool opens orifice P-B when negative signal fed to the T-EHA, which results the cylinder to retract up to 0mm. Motion sensor placed on the T-EHA cylinder will be the input signal for the spool movement as shown in Figure 4.

Fully stroked T-EHA cylinder will fully open the excavator's directional control valve spool. It means 200mm of T-EHA cylinder stroke is equivalent to 5mm of excavator's directional control valve spool movement. Therefore, there should be a variable which indicates the relation between both of them. Therefore, equation 1 is produced:

$$200mm(C) = 5mm \tag{1}$$

where C = 0.025.

In order to relate the motion of the T-EHA's cylinder and excavator's spool movement, a Gain block was placed. Its function as a multiplier for the function in order to complete the signal fed to the excavator's directional control valve. Therefore, the excavator cylinder extends when the T-EHA cylinder extends.

D. Input Signal

Figure 5 shows the input signal assigned to the system indicates the spool movement of the T-EHA's directional control valve. Therefore, the maximum and minimum value of the signals are $\pm 0.005\, m$. Positive signal was given for the first 4 seconds, which allows the spool to open orifices P-A and B-T.

Negative signal was fed to the system after 5 seconds of simulation until 9 seconds, opening orifices P-B and A-T.

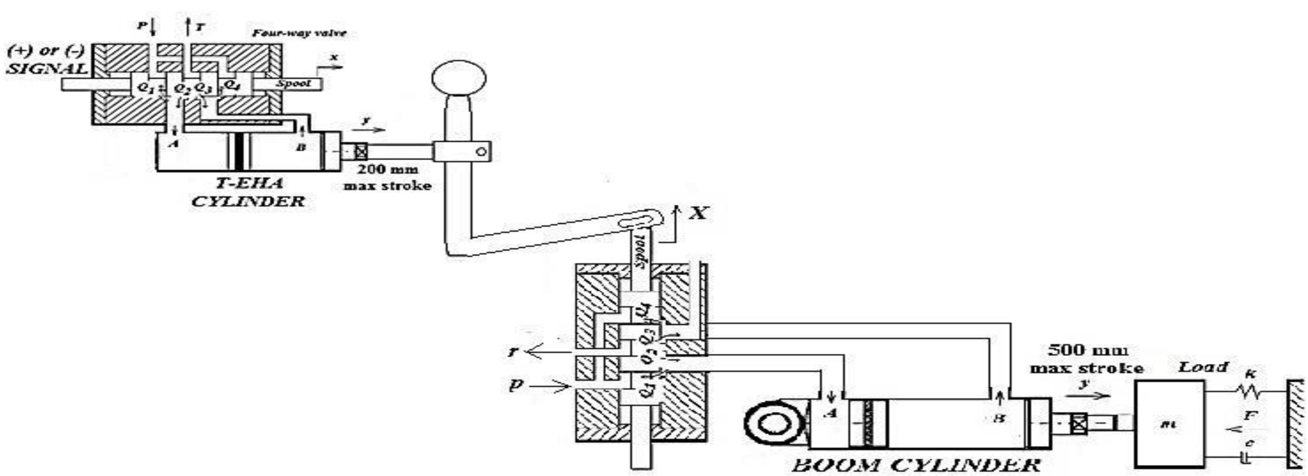

Figure 3: T-EHA and Excavator Working Mechanisms

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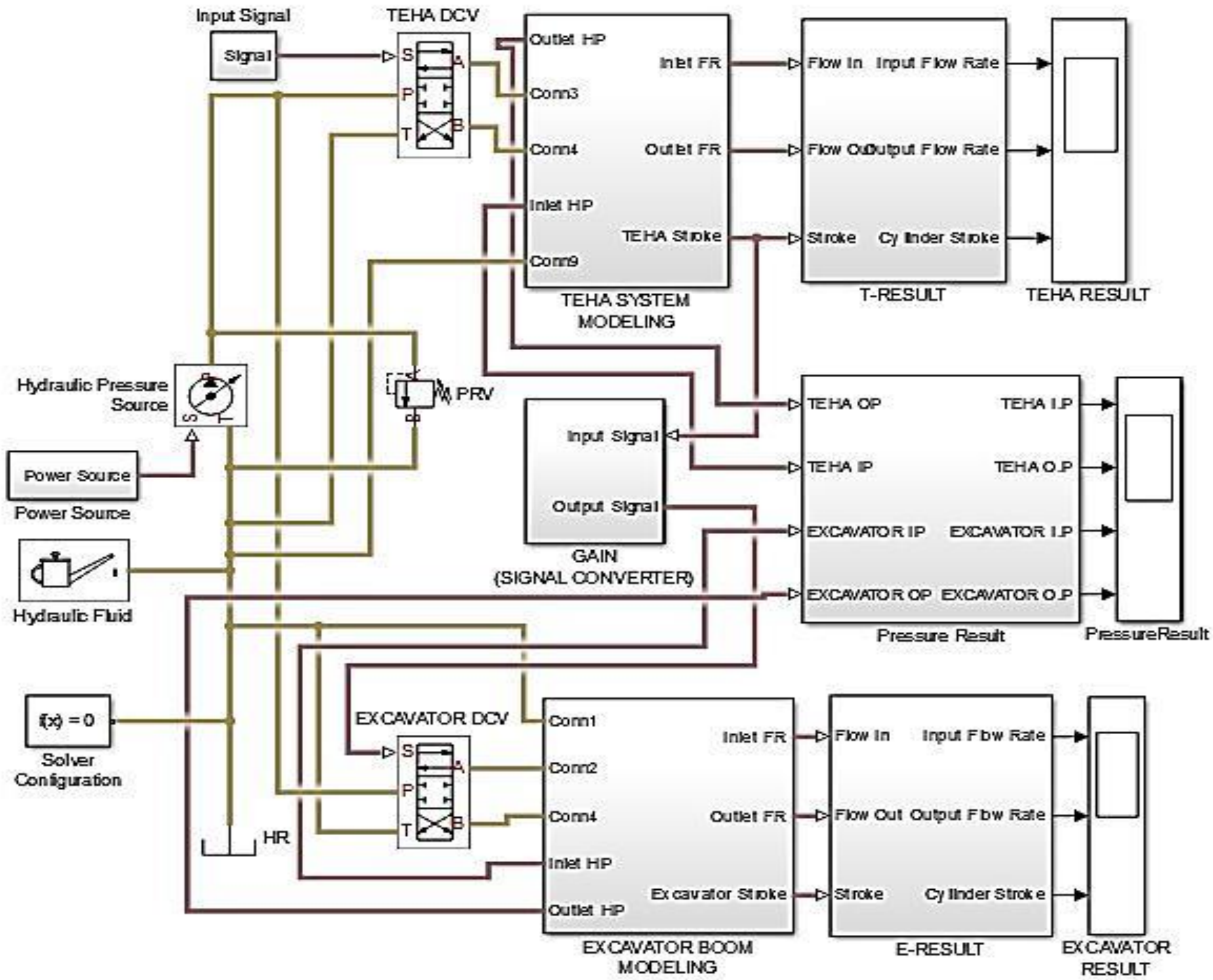

Figure 4: Entire T-EHA and Excavator SimScape Modeling

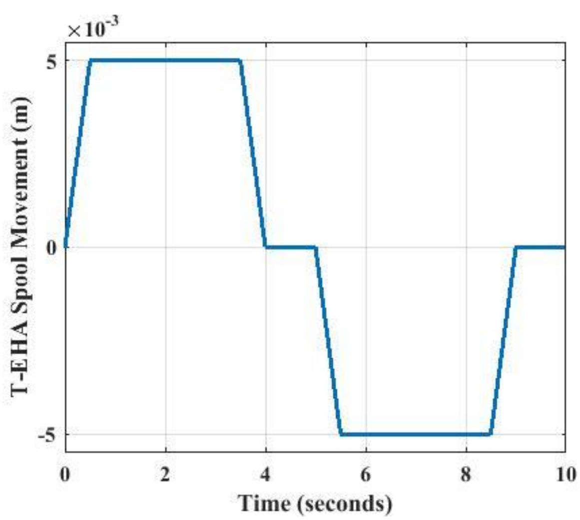

Figure 5: Input Signal fed to the system

III. Results and Discussion

The simulation focuses on some hydraulic and mechanical characteristics.

A. Spool Movement and Cylinder Stroke

The positive signal fed to the T-EHA's spool allows the TEHA's and the excavator cylinder to extend. By referring to Table 1, the time taken for the T-EHA's spool to move 0.005m is 0.5s. The orifices P-A for the T-EHA's directional control valve is opened for 3.5s. However, the TEHA's cylinder requires 0.7s to extend by 0.1m. By referring to figure 1 and 2, we can see that the pattern of the graph for TEHA's cylinder stroke and excavator's spool movement is the same. This is because the excavator's spool movement is directly proportional to the TEHA's cylinder stroke.

Therefore, the time taken for the excavator's spool to move 0.005m is 0.7s. Negative signal input was fed to the T-EHA's spool after 5 seconds of simulation. It took 0.5s for the spool to fully open orifices P-B which allow the T-EHA's cylinder to retract. The time taken for T-EHA's cylinder to retracts to the initial position (centre) and fully retracts is 0.68s and 1.11s respectively. The time taken from the T-EHA's cylinder to fully retract is longer compared to fully extend (referring to the earlier condition) due to the length of stroke required to fully retract which is 0.2m.

The excavator's cylinder starts to retract when the T-EHA's cylinder begin to retract from its initial position (centre). It took 2.37s for the excavator's cylinder to fully retract. Figure 6 (a) shows the spool movement for both T-EHA and excavator directional control valve spool movement, meanwhile Figure 6 (b) shows the length of stroke for T-EHA and boom cylinder.

Table 1
Result of spool movement and cylinder stroke

	Maximum length (m)	Time taken to fully extend (sec)	Time taken to fully retract (sec)
T-EHA Spool Movement	0.005	0.5	0.50
T-EHA Cylinder Stroke	0.100	0.7	1.11
Excavator Spool Movement	0.005	0.7	1.11
Excavator Cylinder Stroke	0.500	0.7	2.37

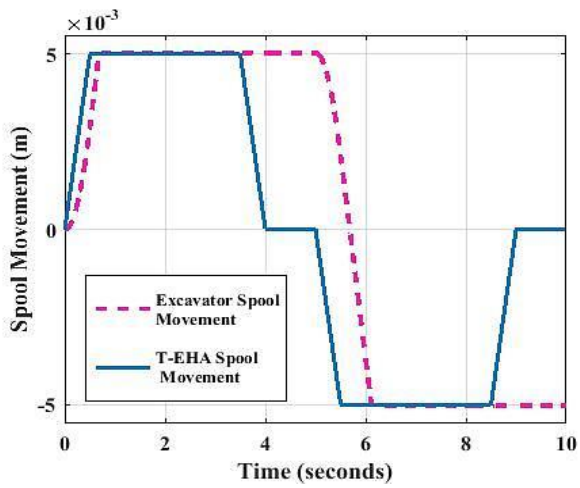

Figure 6 (a): Spool Movement

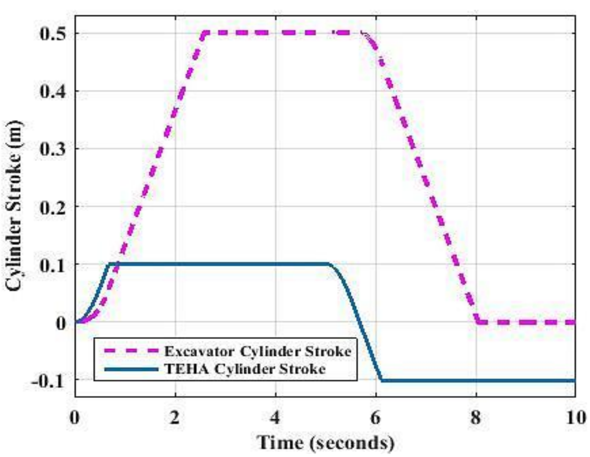

Figure 6 (b): Cylinder Stroke Length

B. Inlet and Outlet Flow Rate

The orifices P-A for the T-EHA's directional control valve is opened when the positive signal is fed to the T-EHA's spool as shown in Figure 7, thus allowing the hydraulic fluid to flow through the system. The flow rate of inlet and outlet of T-EHA increase until the T-EHA's spool reaches its maximum movement. Based on Figure 8 (a) and (b), the flow rate is constant at the rate of $0.29m^3/s$ and then stop when the T-EHA's cylinder is fully extend. Therefore, there is no more hydraulic fluid flowing through the T-EHA system at the period.

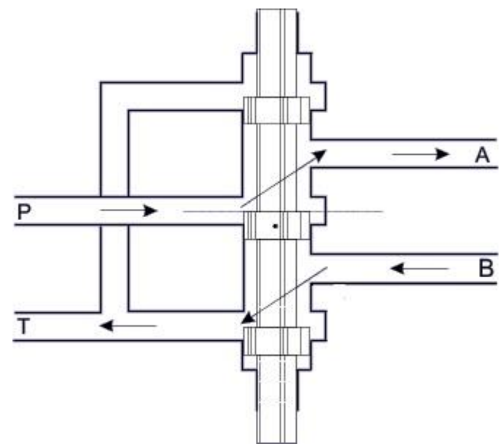

Figure 7: Illustration of Spool Movement

The same situation happened to the flow rate at the excavator system. The flow rate at the excavator's directional control valve increasing until the excavator's spool move to the maximum length. The fluid begins to flow at a constant rate of $0.29m^3/s$. The excavator's cylinder still extending until fully stroke, preventing the hydraulic fluid to flow through the system, thus causing the flow rate to drop to. The fluid begins to flow to the entire system when the T-EHA's spool move to the other side, opening orifices P-B which causing the T-EHA cylinder to retract, thus increasing both T-EHA's and excavator's flow. The fluid flow at a constant rate of $0.29m^3/s$ through the T-EHA system and stop once the T-EHA's cylinder fully retract. However, the fluid still flowing through excavator system and begin to flow at a constant rate of $0.29m^3/s$ once the excavator's spool reach its maximum opening length. The fluid stop flowing once again when the when the excavator's cylinder is fully retracted.

C. Inlet and Outlet Pressure

The pressure at both inlet and outlet port of the cylinder for T-EHA and excavator increase when the T-EHA spool moved due to the signal fed as shown in Figure 9 (a) and (b). However, the pressures exerted at both systems become a constant value of 3 MPa due to the equivalent pressure distribution at the inlet and outlet of the cylinders. This is because the pressure of the system was set to be 6 MPa. By observing Figure 9 (a) and (b), the inlet pressure for the T-EHA system increases to 6 MPa because the cylinder is fully extended, disabling the fluid to flow through the cylinder. However, there is no pressure exerted at the outlet of the cylinder because the fluid is flowing through orifices P-A from port P to port A. Same condition happened to the excavator system The pressure stop increasing and become constant at 3 MPa until the excavator cylinder is fully extended.

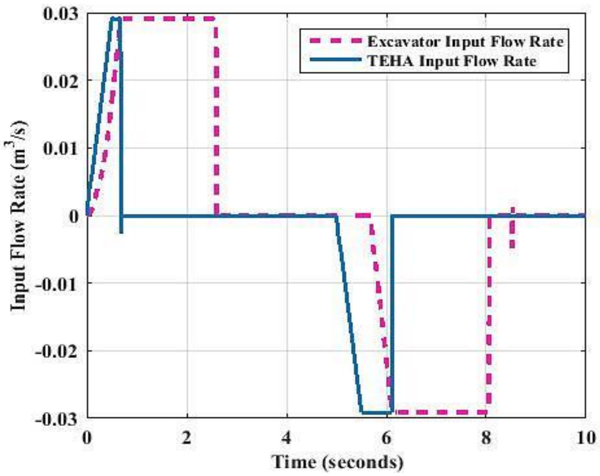

Figure 8 (a): Inlet Flow Rate

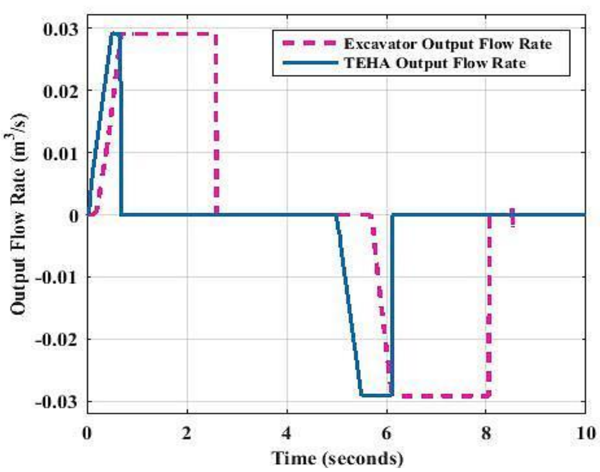

Figure 8 (b): Outlet Flow Rate

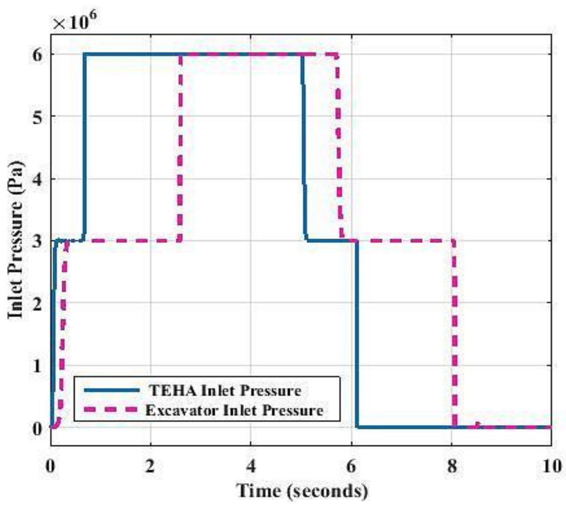

Figure 9 (a): Inlet Pressure

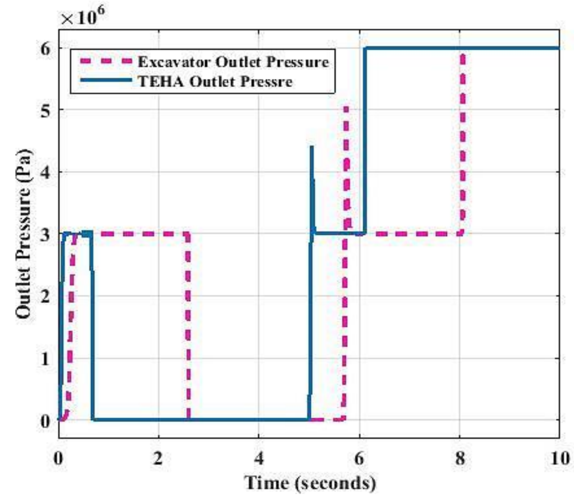

Figure 9 (b): Outlet Pressure

The pressure reaches its maximum value of 6 MPa once the cylinder is fully stroke. There is also no pressure exerted at the outlet of the excavator's cylinder due to the same cause referring to the T-EHA's cylinder. The inlet pressures decrease while the outlet pressures increase for both systems once the cylinders start to retract until it become constant at a value of 3 MPa. The outlet pressure of for both cylinder increase to 6 MPa while the inlet pressures decrease to 0 MPa once their relative cylinder is fully stroke. This happened due to the same reason when both cylinders have been fully extended. The pressure relief valve is opened when one of the situation below occurred;

- Inlet pressures is 6 MPa while the outlet pressures is 0 MPa at both cylinders.
- Inlet pressures is 0 MPa while the outlet pressures is 6 MPa at both cylinders.

IV. CONCLUSION

In the study, it can be concluded that the valve passage maximum area at the directional control valve which is $5 \times 10^{-4}\ m^2$, is the main characteristic that will affect the flow rate for the entire system. The existence of pressure relief valve is very important in order to prevent the pressure of the entire from increasing when both cylinders are fully extended and retract, which are $+100\ mm$ and $-100\ mm$ respectively, from the initial position (center). In the future work, the simulation will include the overall T-EHA and excavator hydraulic system, including boom, arm, swing and bucket. Furthermore, an experiment will be conducted by including the overall operation of T-EHA and mini excavator.

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