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DEVELOPMENT AND EVALUATION OF HYDRAULIC SIMULATION MODEL FOR WHEEL LOADER

Khairul Alam[1], S. Hee Park[2], C. Don Lee[3] and S. Yong Yang[3]

[1]Graduate School of Institute of e-vehicle Technology,
[2]Graduate School of Mechanical and Automotive Engineering,
[3]School of Mechanical and Automotive Engineering,
Republic of Korea

ABSTRACT
This paper presents the development of a simulation model for wheel loader hydraulic system. Using the AMESim programming environment as a simulation tool, each component of wheel loader hydraulic system such as main pump, main control valve, compensator, joystick and attachments are modeled according to their specifications and the total simulation model is obtained by a combination of these component models. Analysis and simulation results show that our developed model can simulate wheel loader hydraulic system and its components effectively.

Keywords: Hydraulic system, Simulation, Wheel loader.

1. INTRODUCTION
Advancement of simulation capabilities made it possible to simulate any physical system before building the prototype to evaluate controls and performance test of components. Simulation results help to improve the design, reliability and operability, thereby reducing cost and time associated with the design significantly. Although hydraulic systems exhibit severe hysteresis and system discontinuities which are often responsible for inaccurate operation, simulation plays an important role in many applications. Therefore, this paper concerns with the development of a hydraulic simulation model for wheel loader.

The wheel loader is a hydraulic machine that has a bucket in the front and can be used for digging, transporting, loading and unloading different type of materials. Wheel loader has obtained popularity in various working fields, especially in urban engineering projects and earthmoving works. Consequently, it has been received much attention by many researchers in order to achieve great gains in efficiency, performance, safety and operator comfort [1-2]. Moreover, an operator of such a vehicle needs a lot of training time and experiences until he can handle a vehicle safely and skillfully. In order to reduce these requirements for the operator as well as to protect from the hazardous working environment, a vehicle should be made as more autonomous way [3]. This work focuses on as a first step in this direction, a wheel loader hydraulic circuit modeling and simulation program to evaluate automatic loading and unloading task.

A wheel loader consists of variable displacement tandem axis piston pump which is load sensing control type along with maximum pressure regulator, and is operated by signals from joystick that control pilot pressure to spools of the main control valve (MCV). The MCV consists of boom and bucket. Several kinds of hydraulic control systems such as valve control as well as pump control have been examined. Among these, load sensing based pump control system has shown most effective with the control problem of hydraulic wheel loader system. Another remarkable point of this work is to apply flow sharing principle to prevent work stoppage during simultaneous operation of actuators. On the basis of this appropriate and reliable model, wheel loader hydraulic system components can be designed and further optimized conveniently, which can reduce costs.

The remainder of this paper is organized as follows: Section 2 presents description of wheel loader sub-systems. In the following section modeling of hydraulic system including each component's model using AMESim are shown. The results of simulation are in the section 4. Section 5 contains a summary of the work.

2. WHEEL LOADER SUB-SYSTEMS
Wheel loaders can be divided into four sub-systems: (1) power-train, (2) brakes, (3) steering (4) hydraulic system for actuators as shown in fig. 1.

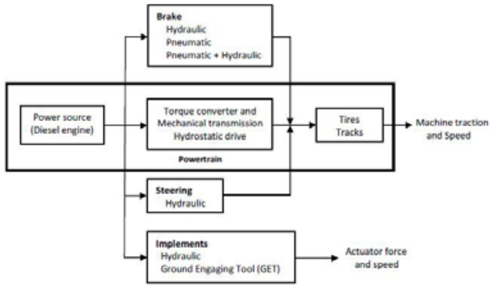

Fig 1. Block diagram of wheel loader sub-systems [1]

The power-train consists of a power source which is typically a diesel engine. Power is transmitted to a mechanical transmission via a torque converter which then connects to differentials, drives and finally tires. Several engine power take-offs provide power via pumps to run the steering hydraulic system, the brake system, and the hydraulic actuation system. The hydraulic actuation system contains the ground engaging tools (attachment) that provides the force and motion to engage the pile that needs to be processed. This paper concerns with the modeling and simulation of hydraulic system. The steering system is out of this paper scope. Figure 2 shows the structure of the simulation model.

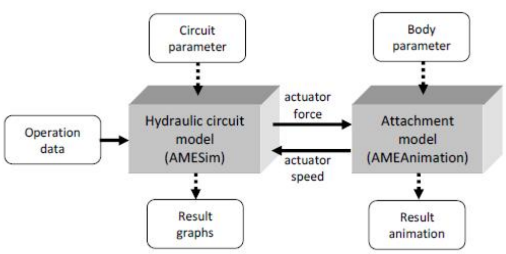

Fig 2. Structure of the simulation model

3. HYDRAULIC SYSTEM MODELING

In order to develop the simulation model, at first the main components of a wheel loader hydraulic circuit such as main pump, MCV, compensator, joystick and attachment are modeled using AMESim, a leading commercial simulation software in the field of hydraulic system. These components modeling are based on typical 23-26 ton hydraulic wheel loader.

3.1 AMESim Software Environment

AMESim is multidisciplinary modeling, simulation and analysis software that allows to link between different physics domains as hydraulic, pneumatic, mechanic, electrical, thermal, and electro-mechanical. It was a product of Imagine Corporation of France, and was acquired in June 2007 by LMS International. It has rich module libraries, which can be extended according to demands. Modules are used in accordance with the actual physical system to build simulation model without having to deduce the complex mathematical model. In order to reduce simulation time and improve the accuracy of simulation, its intelligent solver can automatically select the best integration algorithm from the seventeen algorithms according to the mathematical features of model. AMESim has several interfaces with other computing software like Simulink, Adams, Simpack and dSPACE. In this paper the simulation program is developed using AMESim 4.3.0 version.

3.2 Main Pump Modeling

The main pump modeled in this paper is variable displacement dual tandem axis piston pumps having pump displacement 100 cc/rev and 51 cc/rev respectively with load-sensing controller and maximum pressure regulator.

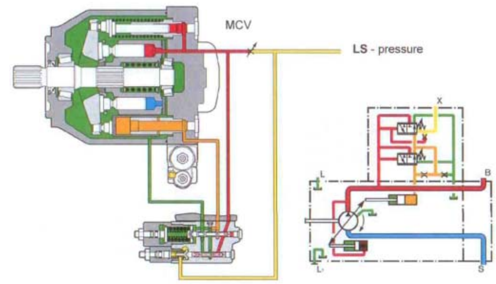

Fig 3. Cross-section of a typical variable displacement load-sensing pump

A load-sensing pump is actuated in dependence on the highest load pressure and only produces the flow demanded by the actuators that makes it energy efficient. Figure 4 shows the AMESim model of one section of the main pump.

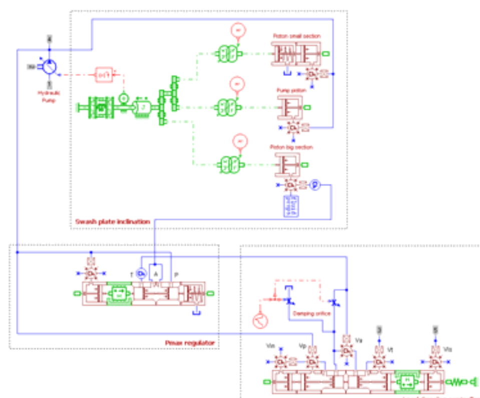

Fig 4. Model of the main pump using AMESim

The pump swept volume is a function of the inclination of the swash plate. The swash plate angle is governed by the resulting torque given by the piston small section, pump pistons and the piston big section, controlled by the flow rate given by the load-sensing controller together with maximum pressure regulator. The main dual tandem pump is formed by coupling two pump sections with single motor having shaft speed 2300 rev/min.

3.3 Joystick Modeling

The employment of joysticks has virtually replaced the traditional mechanical control lever in nearly all modern hydraulic control systems. Most of the movements of wheel loader are controlled with operation of joystick control lever. Joystick operation decides pilot pressure and direction of movements of MCV spools. The pilot pressure having range 0~45kgf/cm^2 is used in this hydraulic system simulation model. This pressure acts on either side of MCV spools, results respective displacement of spools. Then hydraulic oil passes through the flow area generated by the movement of spools.

In this paper, the operating signal input to joystick is assumed between -10 to 10 and the corresponding pilot pressure generated to port A and port B is directly proportional to the magnitude of input signal. Figure 5 shows the AMESim model of the joystick.

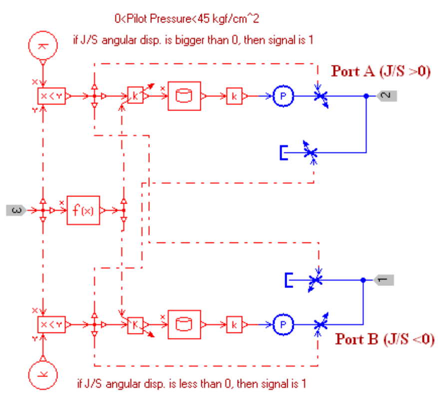

Fig 5. Model of the joystick using AMESim

3.4 MCV Modeling

The MCV consists of various valves for boom, bucket and auxiliaries. Only the valves for boom and bucket are modeled in this paper. These valves are 8 ports 3 position types including bypass line as shown in fig. 6.

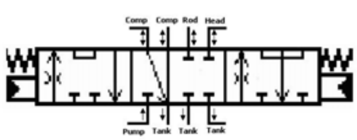

Fig 6. Circuit diagram of boom valve

When pilot pressure acts on one side of a valve selectively, spool is moved in accordance with the pressure. Then the flow area with respect to spool displacement shows a non-linear relation that shown in fig. 7. In course of modeling of MCV valves, the factors considered are the stroke of spool, the mass of spool, the flow area with respect to spool displacement, the diameter of spool, and the end spring stiffness. The model of valves comes from mechanical and hydraulic component design module libraries of AMESim. The valve modeling for bucket is done in a similar way as boom valve. Figure 8 shows the AMESim model of the boom valve.

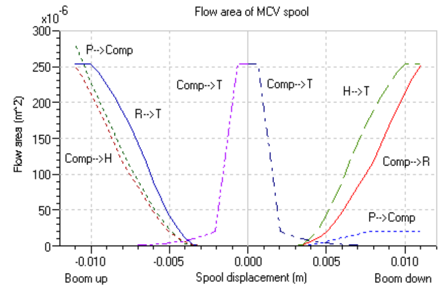

Fig 7. Spool displacement-Flow area characteristics of the boom valve

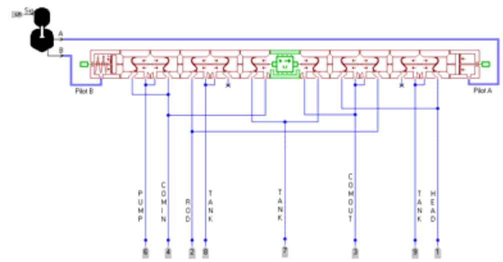

Fig 8. Model of the boom valve using AMESim

3.5 Compensator Modeling

The compensator arranged downstream from the orifice (valve spool) is subjected to the pressure downstream from the respective orifice in the opening direction and in the closing direction to a pressure from the respective actuator. It keeps the pressure drop across the orifice constant, which keeps flow constant and thereby cylinder speed is constant independent of load. Figure 9 shows the hydraulic circuit model of compensator.

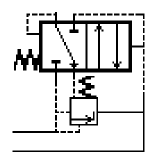

Fig 9. Circuit model of compensator

The compensator keeps the pressure in the pump line to a higher value than the highest load pressure by a pressure difference equivalent to the force of a control spring, so-called Δp control. The value of Δp is assumed to 20 Bar in this paper. Figure 10 shows the AMESim model of compensator.

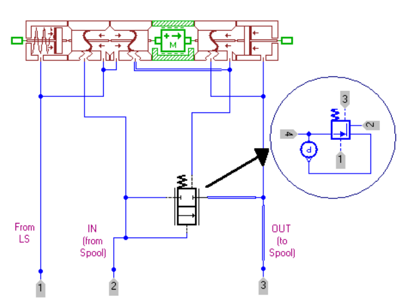

Fig 10. AMESim model of compensator

3.6 Attachment Modeling

There are several types of wheel loader implement linkages currently in use. A very common example, called the Z-bar linkage [1], is shown in Fig. 11.

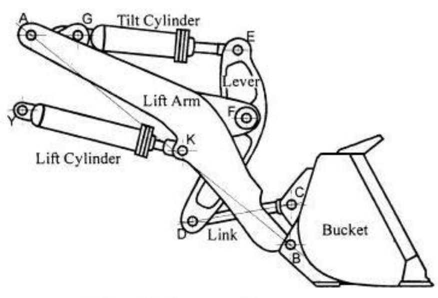

Fig 11. Typical wheel loader attachment

It is a two degrees of freedom (dump and roll back) linkage consisting of four bodies (lifting arm, reversing lever, connecting link, and bucket) and two asymmetric hydraulic cylinders (lift and tilt), all connected together by nine revolute pin joints. The tilt and lift cylinders are double acting type and the specifications are shown in table 1.

Table 1: Specification of cylinders

Parameter	Lift cylinder	Tilt cylinder
Piston diameter	175 mm	150 mm
Rod diameter	50 mm	55 mm
Length of stroke	760 mm	460 mm
Free length	1240 mm	800 mm

In the course of modeling of the Z-bar linkage using AMESim, the size and weight of the bodies are obtained from the specifications of a typical wheel loader. The position of the bodies has defined according to the relative coordinate system of the AMESim planar mechanical library. In order to get actual animation at desired shape of the attachment, this model includes contour data of reversing lever, lifting arm and bucket that confirm the virtual movement of the attachment based on simulation result. Figure 12 shows the AMESim model of the attachment.

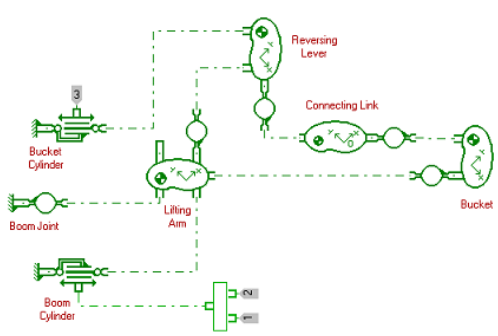

Fig 12. Model of the attachment using AMESim

3.7 Total Hydraulic System Modeling

By a combination of models, including the model of pump, MCV spools, compensators, and attachment, coupled with input signal, we get the complete simulation model of the wheel loader hydraulic system, as shown in fig. 13.

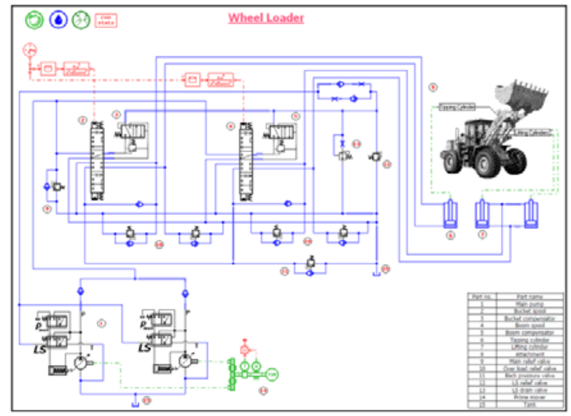

Fig 13. Wheel loader hydraulic system simulation model using AMESim

Simulation runs are carried out to verify the effectiveness of the proposed simulation model when it is applied to wheel loader hydraulic system with different joystick input signals. An additional advantage of this model is that we can rectify the simulation results more quickly and easily by the animation function.

4. SIMULATION AND RESULTS

This simulation program works according to the operation of joystick control lever that moves MCV spools. We considered virtual loading and unloading tasks. Then the operating signals input to joystick are assumed between -10 to 10, as shown in fig. 14.

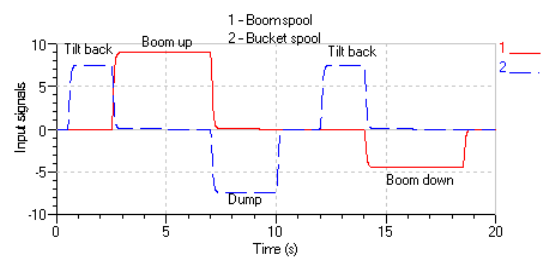

Fig 14. Joystick signals

The movement of attachment according to input signals is decided same order as illustrated in Table 2.

Table 2: Cylinder movement with respect to input signal

Signal	Boom	Bucket
+ (positive)	up	tilt back
0 (zero)	hold	hold
- (negative)	down	dump

A variety of graphs are obtained from the simulation results. Figure 15 shows results for the main pump namely pump pressure and pump flow rate.

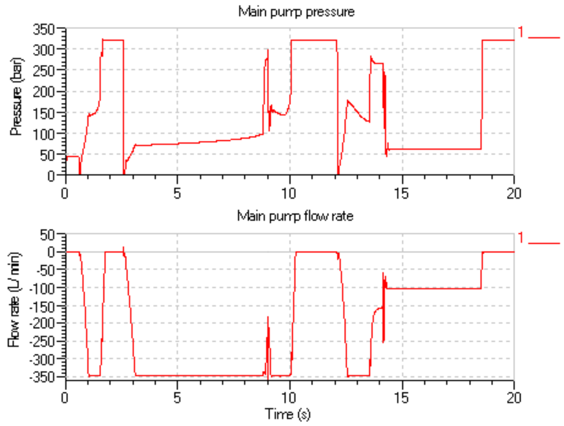

Fig 15. Simulation results of main pump

Figure 16 shows simulation results for the boom namely pilot pressure for boom operation, boom cylinder displacement, pressure and flow rate for boom cylinder head and rod side respectively.

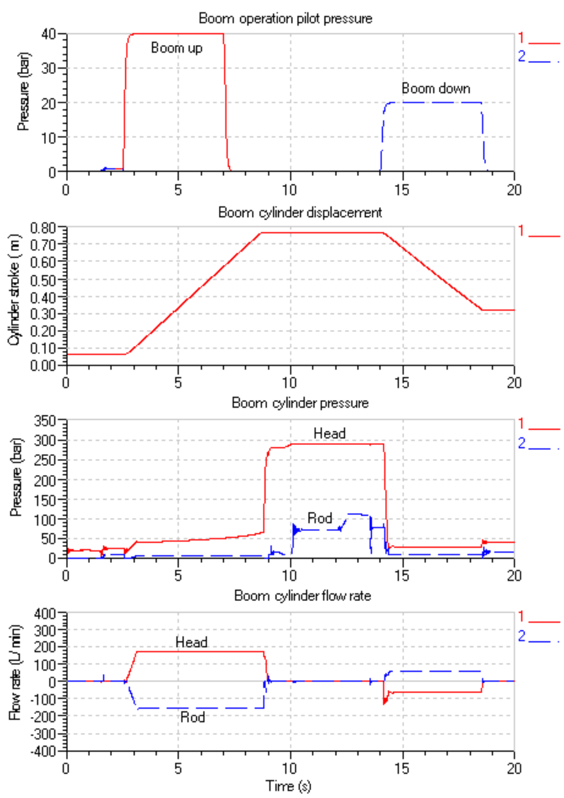

Fig 16. Simulation results of boom

Figure 17 shows simulation results for the bucket namely pilot pressure for bucket operation, bucket cylinder displacement, pressure and flow rate for bucket cylinder head and rod side respectively.

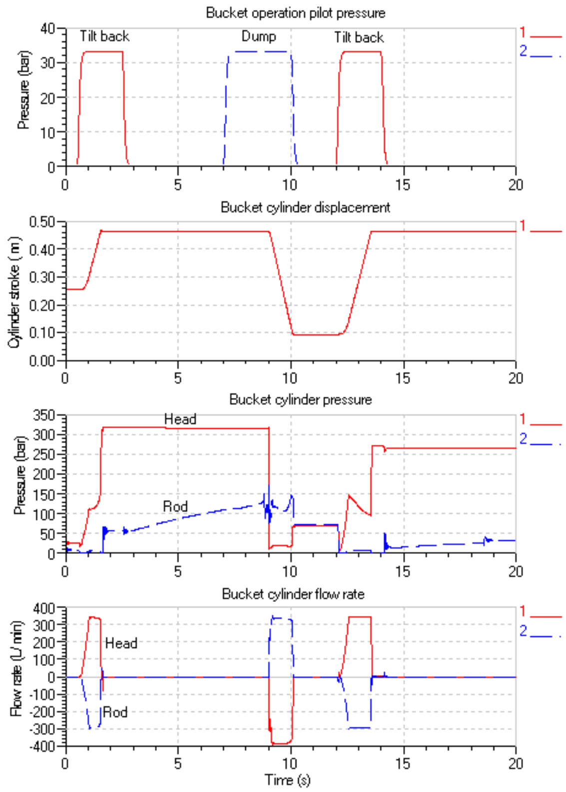

Fig 17. Simulation results of bucket

Figure 18 shows absolute angular position of the attachment according to boom and bucket cylinder displacement.

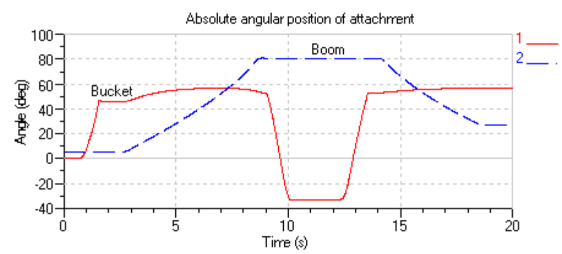

Fig 18. Absolute angular position of attachment

Figure 19 shows attachment model using AMEAnimation based on simulation results.

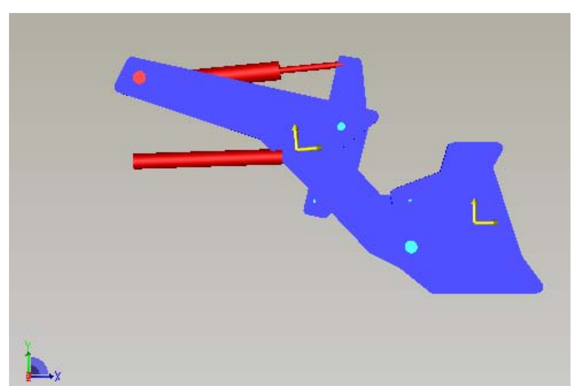

Fig 19. Attachment model using AMEAnimation

In this simulation model the value of Δp is assumed to 20 Bar and it is the compensators' job to fix the pressure drop across the orifice at 20 Bar. As the pressure drop is constant, the flow rate only depends on the valve position. This provides very precise control. Figure 20 and 21 shows the pressure comparison across boom and bucket compensator respectively.

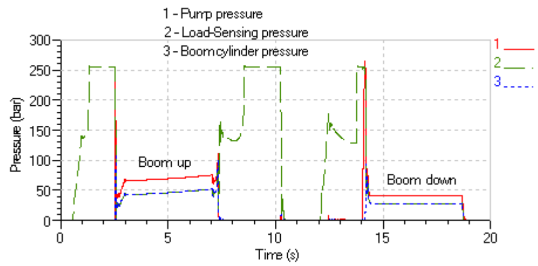

Fig 20. Pressure comparison across boom compensator

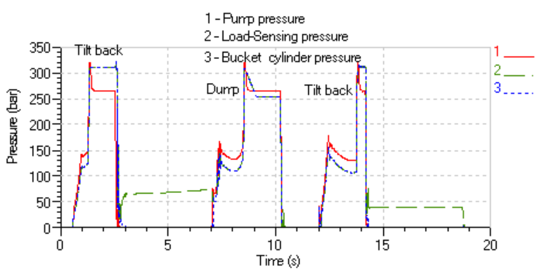

Fig 21. Pressure comparison across bucket compensator

From the above figures we see that the main variable pump adjusts pressure according to load-induced pressure fed back to the pump through load-sensing controller and maintains a higher value equivalent to Δp, thereby making the system energy efficient. Figure 22 shows the result obtained from the field test of a typical wheel loader.

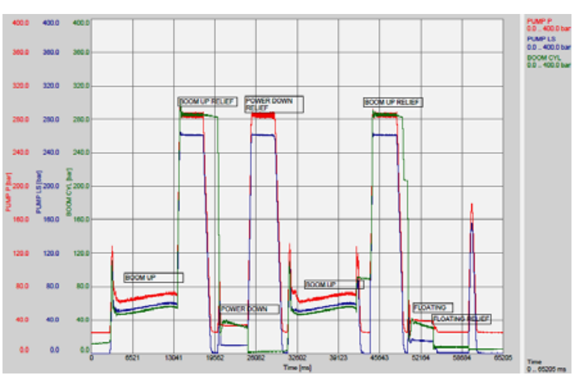

Fig 22. Typical wheel loader experimental test plot

From the Figs. 20-22, obviously, simulation results show a good agreement with experimental results, so the model, as shown in fig. 13, is right.

5. CONCLUSIONS

The conclusions of this work are as follows:

1. The developed simulation model can simulate wheel loader hydraulic system and its components effectively. Results of simulations can be used as initial data while building trial versions of real hydraulic system models.
2. In this respect it must be pointed out that the pressure drop across the orifice is not exactly 20 Bar as set. As the shape of the graphs depends mostly on the flow areas of the orifice of the valves, it is very difficult to achieve exact pressure drop.
3. The model in this paper can apply a platform to design and optimize the hydraulic system components, which can save time, reduce costs and improve components quality.
4. Along this research frame, as a future step, we intend to further develop this simulation model so that it will be applicable to the performance test of hydraulic components and automation study of wheel loader. This will hopefully lead in the near future to a modeling tool capable of accurate portrayal of the wheel loader hydraulic system.
5. The approach is original and there is difficult to find similar works. The methods of modeling and simulation possess universal significance to other related hydraulic systems.

6. ACKNOWLEDGEMENT

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7. REFERENCES

1. Mike Cobo, Richard Ingram and Sabri Cetinkunt, 1998, "Modeling, identification, and real-time control of bucket hydraulic system for a wheel type loader earth moving equipment", *Mechatronics*, 8-8:863-885.
2. Sarata, S., Weeramhaeng, Y. and Tsubouchi, T., 2005, "Approach Path Generation to Scooping Position for Wheel Loader", *IEEE Conference on Robotics and Automation, ICRA 2005*, pp.:1809-1814.
3. Soon-Young Yang, Sung-Min Jin and Soon-Kwang Kwon, 2008, "Remote control system of industrial field robot", 6th*IEE International Conference on Industrial Informatics, INDIN 2008*, DOI 10.1109/INDIN.2008.4618140, pp.:442-447.
4. Sung Hee Park, Khairul Alam, Young Man Jeong, Chang Don Lee and Soon Yong Yang, 2009, "Modeling and Simulation of Hydraulic System for a Wheel Loader using AMESim", *Proceedings of the ICCAS-SICE2009, ICROS-SICE International Joint Conference*, August 18-21, Fukuoka, Japan, pp.:2991-2996.
5. Kazuhide Maehata, "System Simulation for Hydraulic Excavator", 2008, 7th *JFPS International Symposium on Fluid Power, TOYAMA 2008*, 2:313-316.
6. AMESim solutions guide, 2008, LMS Imagine. Lab, LMS Engineering Innovation.