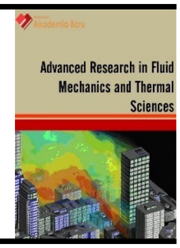
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Analysis of Water Hammer in Water-based Hydraulic Actuator System

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ARTICLE INFO

Article history:
Received 12 February 2018
Received in revised form 12 May 2018
Accepted 4 June 2018
Available online 15 June 2018

Keywords:
Microgels, emulsion polymerization, hydrogel, copolymer

ABSTRACT

This study proposes a hydraulic pressure transient analysis of a low-cost water hydraulics actuator system. The objective of this project is to study the performance of the actuator under various circumstances. Water hammer is a problem that happened to all type of pipe that has the fluid flow on it. It is due to the pressure difference in the pipe which happened when the velocity of the fluid flow is suddenly stopped due to a closed valve. This effect will cause the damage to the pipes when the pressure exceeding the maximum pressure that can withstand for the pipe. The analysis of the water hammer is done to overcome this problem from happen in the pipeline especially in hydraulic system and it needs to create a simulation circuit of the hydraulic system. Simulation has been conducted for pressure at 50 and 100 psi at length of pipe 0.5 and 1.0 m length.

1. Introduction

Water hydraulics encourages the sustainability and environmental friendly approach in power transmission. [1]-[3]. Basically, the aim of using water in hydraulic power system is to transfer the energy, power and the resource sustainably, at a rate that does not compromise the natural environment. Water hydraulics can offer a design for hygiene solution in various industries, as demonstrated by the development of water hydraulics pumps, valves and actuators in the food processing industry, robotics, machineries, waste management and marine application [4]-[10].

This paper focusses in a typical water hammer issues in any water-based hydraulic power system. A change of flow velocity in a hydraulic system will actuate a change in pressure. Generally, surges are the unsteady flows that happens due to a relatively slow flow rate changes. Water hammer, on the other hand, resulted from a fast or rapid flow rate changes. The sudden shutdown of a pump or closure of a valve may cause fluid transients. This may include large pressure variations, local cavity formation, circulated cavitation or bubble flow, vibrations and excessive mass oscillations. These events may significantly impact on subsequent transients in the hydraulic system. A water hammer

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can collapse a water distribution system, and as such it is essential to analyze it to provide an acceptable level of protection against system failure due to pipe collapse or bursting. Thus, the analysis of water hammer in water-based hydraulics actuator is presented in this paper

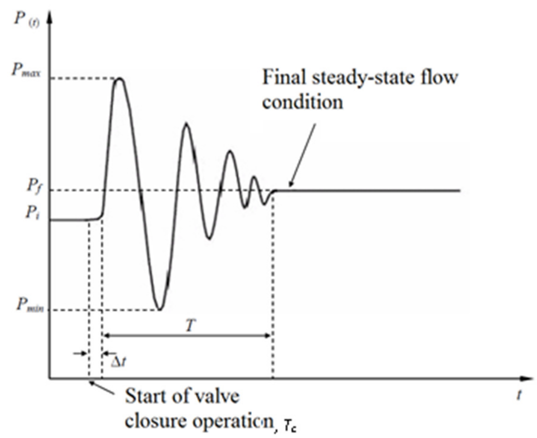

Fig. 1. Water hammer at a designated position

1.1 Water Hammer Phenomenon

Water hammer occurred when the rate of flow is changed quickly or rapidly, for example, flow that going through on the pipeline and the valve is rapid closure or pump stoppages. It is the physical phenomenon that happens during the time interval t between the initial and last steady-state conditions, as shown in Figure 1. The figure shows how the transient evolution in a system looks like and it represents a view of the transient at a fixed point upstream of the valve that is being closed.

The figure diagram explained that the pressure *P* is represented as an element of time, *t*, resulting from the operation of a control valve. In the figure, P_i is the underlying or initial pressure toward the begin of the transient, P_f is the final pressure toward the end of the transient event, P_{min} is the base or minimum transient pressure, and P_{max} is the greatest or maximum hydraulic pressure transient [11]. Such disturbances, regardless of whether brought on by design or accident, may create travelling pressure and large magnitude of velocity waves. These transient pressures are superimposed on the steady-state conditions present in the line at the time the transient pressure happens. The seriousness of transient pressure must be resolved so that the piping can be properly intended or design to withstand these extra and additional loads. [12].

1.2 The Impact of the Water Hammer

In a compressible fluid, water hammer is influenced by the pressure in the pipe, Δ*P,* velocity flow in pipe, Δ*v* and sudden change of velocity flow. This is represented by Joukowsky's equation:

$$\Delta P = \rho c \, \Delta v \tag{1}$$

where ρ is the fluid mass density and c is the speed of sound. The equation expresses that the magnitude of water hammer is directly proportional to the velocity of the wave propagation. Wave propagation velocity depends on the elasticity of the pipe walls and the compressibility of the fluid.

Korteweg's equation characterizes or defines c for liquid contained in round and hollow channels of roundabout cross-segment:

$$c = \sqrt{\frac{K_*}{\rho}} \tag{2}$$

and

$$K_* = \frac{K}{\left[1+\frac{DK}{eE}\right]} \tag{3}$$

where K is the bulk modulus of the contained fluid, E is the modulus of elasticity for the wall, D the diameter of the pipe, and e the thickness of the wall [13]. In the case where the fluid is incompressible, then water hammer can be analyzed by different approaches, which is known as the rigid column theory, which ignores compressibility of the fluid and elasticity of the walls of the pipe. Column separation is a phenomenon that can occur during a water-hammer event, and can be represented by

$$P = \rho v L/t \tag{4}$$

where P is the pressure inside the pipe, ρ is the fluid density, L is the pipe length, v is the velocity flow in pipe and T_c is the valve closure time. Water hammers can cause a pipe network to fail if the transient pressures are too much high. When the pressure is too big than the pressure limits of the pipeline, failure through joints, curves or pipe elbows movement may happen. On the other hand, over the top low pressure/negative pressure can bring about buckling, implosion and leakage at pipe joints during sub-atmospheric stages. Low pressure transients are ordinarily experienced on the downstream side of a closing valve.

2. Hydraulic Actuator

Figure 2. show the hydraulic actuator is represented as a single mass-spring-damper system with a load-disturbance force given by *F.* The mass, spring rate and viscous-drag coefficient for the load are represented by the symbols *m, k,* and *c,* respectively. [14].

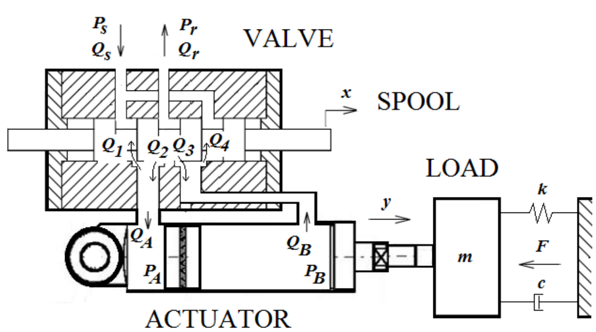

Fig. 2. Hydraulic actuator

The single rod linear actuator is connected to both the load and the actuator piston. The displacement of the spool valve x is shown to be positive in the right direction. When the valve is moved in the positive x direction, hydraulic fluid is directed into side A of the actuator, which then requires the fluid to exit the actuator from side B. The flow rates are represented by the symbols Q_A and Q_B, respectively. The flow is provided by a pump with volumetric displacement V_D, and driven by an electric motor, at rotational speed N. In the mathematical modelling, the resulted pressure transients from fluid compressibility are assumed to be minimum and therefore negligible. This is true for the design that involves a very short transmission lines between the valve and the actuator. The study on hydraulic actuator starts with the basic loading analysis. The inertia of the actuator is neglected in the study. The value is much smaller compared to the actual forces that are generated by the actuator. The equation of motion for the load can be represented by;

$$m\ddot{y} + c\dot{y} + ky = \eta_{af}(A_A P_A - A_B P_B) - F - F_o \quad (5)$$

where PA and PB are the fluid pressures on the A and B sides of the actuator, respectively. The actuator force efficiency is represented by η_{af}. F_o is the nominal spring or bias load that is applied to the actuator when y equals zero. By assuming nominal steady state operating conditions, (y = 0, $P_A = P_B = P_s/2$, and F = 0), it can be shown that during steady state conditions, the nominal force exerted on the actuator by the load is given as;

$$F_o = \eta_{af}(A_A - A_B)P_s/2 \quad (6)$$

3. Methodology

The water hammer occurred when the flow is suddenly closed at high velocity. Thus, a simulation is conducted to predict the occurrence of the water hammer. Two variables are used in obtaining the data and determining the main factor that caused the water hammer in the water hydraulics actuator system. The parameters are the system pressure of fluid and the length of the pipeline used.

Based on Figure 3, the simulated circuit consists of a pump, a prime mover, a pressure gage, a valve, two pressure sensors and one flow rate sensor at the tested pipe length. The pressure sensors are located in between the tested pipe with certain length setting. The location of the sensors is important to determine the different value of the initial fluid pressure and final fluid pressure. The flow rate sensor will show the actual flow that happen in the circuit while the water hammer occurred. The obtained data is based on the simulated value of the parameters, which is the amount of pressure, types of fluid and the length of the pipeline. The exact amount will be gained, and it can be easily calculated by using the simulation on MATLAB.

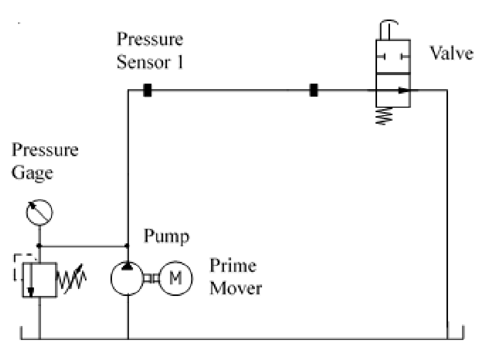

Fig. 3. Simulated hydraulic circuit

3.1 System Parameter

In the simulation, the value for diameter of pipe, d, thickness of the pipeline, e, and the modulus elasticity, E for this system is fixed, which d = 0.03m, e = 1.25mm and E = $2x10^{11}$ Nm^{-2}.

3.1.1 Fluid pressure

Pressure is the main factor that is required to be observed when the water hammer occurred. The pressure inlet is set up at the inlet of the pipe flow to ensure the whole circuit is under the required pressure. Two pressure values are used in this simulation, to observe the occurrence of water hammer. The pressure is set as the controlled variable of the simulation, with respective value of 50 and 100 bar. The maximum pressure during the occurrence of water hammer will involve the subtraction with one of these two pressure inlet value and depend on the system pressure setting. The biggest difference that is gained between both pressure inlets will lead to a very high impact for water hammer.

3.1.2 Pipeline length

Hydraulic circuit is connected from one part to the others by using the pipeline to make the fluid flows through the circuit. Length of the pipeline is one of the factor that cause the different value of pressure in the hydraulic circuit. For this simulation, the pipeline is designated as the manipulated variable, with different length of the pipeline at 0.5 and 1 meter.

3.1.3 Types of fluid

The types of fluid will also influence the water hammer. Fluid is the form of liquid state has their own properties. The major properties that will be considered in the test is density, bulk modulus and thermal conductivity. These properties will affect the outcome of the test.

4. Results and Discussions

4.1 Water Hammer at 50 bar Pressure

Water hammer simulation data was obtained and recorded in form of graph. The simulation results of water hammer is shown in Figure 4 to Figure 7. Figure 4 and Figure 5 shows the influence of length to system pressure set at 50 bar. Figure 6 and Figure 7 shows the same influence of length at 100 bar pressure. Figure 4 shows that water hammer will occur when the flow of the fluid suddenly closed, and the pressure of that space will automatically increase. In this system, the maximum pressure P_{max} is 51.25 bar at t = 0.6s. Unsteady state occurs for 0.01s, before the system reaches steady state at t = 0.61s. The initial pressure during the closure of the valve is measured at 29 bar. This value is not shown in Figure 4, since the initial pressure is recorded at t = 0.5s. In Figure 5, maximum pressure P_{max} is at 52.5 bar, when t = 0.6s. The unsteady state occurs for 0.02s, before reaching the steady state at t = 0.62s. From the data obtained, we can conclude that the pipe with the 1m length at 50 bar pressure will produce a larger water hammer effect.

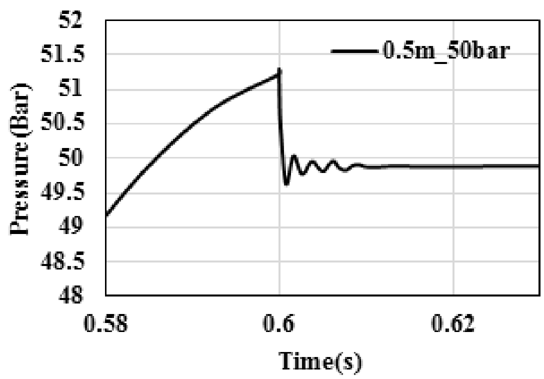

Fig. 4. Water hammer for 0.5 m pipe at 50 bar

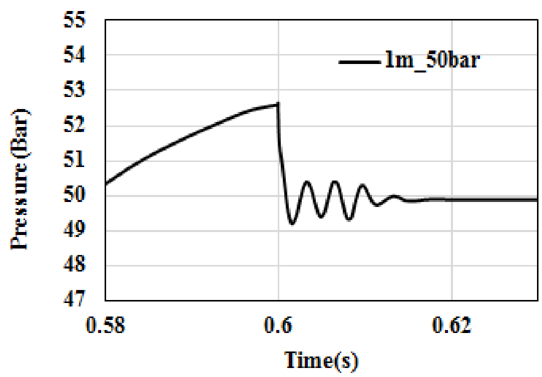

Fig. 5. Water hammer for 1 m pipe at 50 bar

4.2 Water Hammer at 100 Bar Pressure

Figure 6 and Figure 7 show the influence of length at 100 bar pressure. Water hammer will occur at t = 0.5 s (not shown in the Figure) when the flow of the fluid suddenly closed, and the initial pressure of 60 bar will automatically increase. In this system, the maximum pressure P_{max} is 101.8 bar at t = 0.6s.

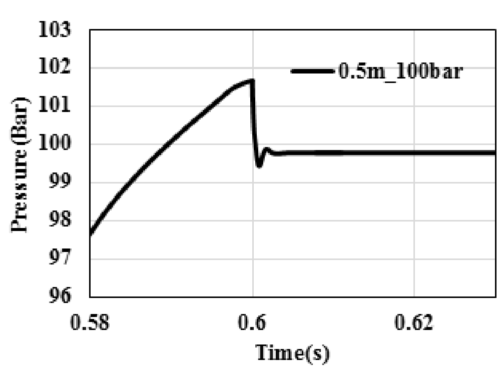

Fig. 6. Water hammer for 0.5 m pipe at 100 bar

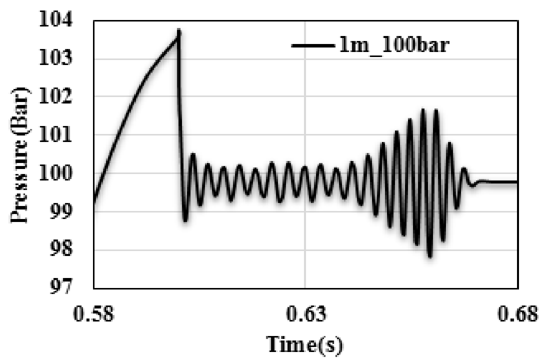

Fig. 7. Water hammer for 1m pipe at 100 bar

The unsteady state is small, before the system reaches steady state at t = 0.605s. In Figure 7, maximum pressure P_{max} is at 103.8 bar, when t = 0.6s. The unsteady state occurs for a longer period of 0.07s, before reaching the steady state at t = 0.67s. From the data obtained, we can conclude that the pipe with the higher length at 100 bar pressure will produce pressure increased over 100 bar pressure on water hammer effect.

5. Conclusions

This paper has successfully demonstrated the performance of the hydraulic actuator under various circumstances. It is concluded that the extension of pipeline will increase 1.0% - 2.0% the chances of water hammer depends on the system pressure. The effect is greater at a higher system pressure. The best water hydraulics actuator should be fabricated with the shortest transmission line possible to lower the probability of water hammer phenomenon.

Acknowledgments

This work was funded by Ministry of Higher Education (MOHE) of Malaysia, under the Fundamental Research Grant Scheme (FRGS). FRGS/1/2016/TK03/FKM-CARE-F00317. The authors wish to thank Ministry of Higher Education and Universiti Teknikal Malaysia Melaka for their support.

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