Simulation Research on System Characteristics of Valve Opening Curve of Bidirectional Water Transfer System

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Abstract. Due to long pipelines, complex hydraulic conditions, and high flow rate, Bidirectional Water Transfer System of ship is prone to producing Water Hammer Effect when the valve opens and closes, which has a great impact on the pipeline system. In this paper, Flowmaster software is used to simulate the Bidirectional Water Transfer System to study the system characteristics under different valve opening curves. The simulation results show that when the valve opens and closes, Bidirectional Water Transfer System will have a large pressure mutation. But the pressure changes of the stepped and the stepped curve opening curves are smaller and smoother than that of the linear opening curve. But the stepped and the stepped curve opening curves can’t eliminate the pressure and flow rate mutation when the valve opens and closes; In addition, the stepped and the stepped curve opening curves can effectively improve the phenomenon of water flowing out of the reservoir, and effectively avoid the phenomenon of gas flowing into the reservoir.

1. Introduction

The rapid change of the fluid flow rate in the pressure pipeline will cause the pressure fluctuation in the pipeline, which will lead to the rapid change of the fluid momentum, and then the pressure in the pipeline fluctuates suddenly. This is called Water Hammer Effect [1,2]. The Bidirectional Water Transfer System is commonly used in ships to adjust the trim angle of the ship's bow and stern so as to keep balance. The Bidirectional Water Transfer System transfers the water from Reservior 1 to Reservior 2 by injecting high-pressure air [3-5]. Due to high flow rate, complex hydraulic conditions, etc., a very serious Water Hammer Effect occurs when the valve opens and closes which will produce large impact, vibration and noise to the pipeline system, and even damage the piping components in the system [6].

Aiming at the influence of the valve opening curve on the characteristics of the Bidirectional Water Transfer System, this paper uses the Flowmaster software to model the Bidirectional Water Transfer System. By using a Four-Way Valve to simulate water discharging from the water reservoir, inflowing into water reservoir or self-circulation. This paper circulates the system characteristics of different valve opening curves and analyzes the influence of the valve opening curve on the characteristics of the Bidirectional Water Transfer System.

2. Bidirectional Water Transfer System

2.1. Principle of Bidirectional Water Transfer System

The Bidirectional Water Transfer System has water circuit and air circuit.

The water circuit consists of the Four-Way Valve (substituting the actual combined valve structure for a Four-Way Valve), hydraulic pump, Reservoir 1 and Reservoir 2. The Four-Way Valve plays the role of flow distribution. The flow distribution between the different valve ports of the Four-Way Valve
is controlled by the on-off status of the valve ports. Different status of the valve ports simulate water discharging from water reservoir, inflowing into water reservoir or self-circulation[7]. The opening of the valve port is controlled by the controller; the hydraulic pump is responsible for providing power for the Bidirectional Water Transfer System to ensure the circulation of water between the reservoirs; the Reservoir 1 and 2 is responsible for simulating the reservoirs in ship. In addition, there are lots of auxiliary components such as flow control valves, flowmeters, and stop valves.

The air circuit is composed of several exhaust control valves, air supply regulating valves, exhaust mufflers and other components. And it is connected with the air supply system to control the gas flow and pressure in the reservoirs.

![Diagram of Bidirectional Water Transfer System](image)

### Figure 1: Schematic diagram of Bidirectional Water Transfer System

2.2. Flow state description

According to the on-off condition of the Four-Way Valve, there are three flow states:

#### 2.2.1. State One

In the first state, A and D, B and C are respectively connected. At this time, water flow out from Reservoir 1, through port D and A, flowing through the hydraulic pump, port B and C, finally flowing into the Reservoir 2, as shown in Figure 2;

![Diagram of State One](image)

**Figure 2: state one**

#### 2.2.2. State Two

In the second state, port A and B are connected. At this time, the Reservoir 1 and the Reservoir 2 are both disconnected from the circuit. Because of the hydraulic pump, the water is self-circulating. That is, water flow from port B into the Four-Way Valve, and flow out from port A. Then flow back to port B after being pressurized by the hydraulic pump, as shown in Figure 3;
2.2.3. **State Three**

In state three, A and C, B and D are respectively connected. At this time, water flow out from Reservoir 2, through port C and A, flowing through the hydraulic pump, port B and D, finally flowing into the Reservoir 1, as shown in Figure 4.

2.3. **Flow distribution of Four-Way Valve**

The above three states do not exist in isolation from each other. The process between states is continuous, and there are two transition processes when state one to state two and state two to state three.

If the external conditions do not change, the flow of the A and B ports during the two transitions is a constant value, that is \(QA=QB=QBA+QDA=QBA+QCA=\text{const.}\)

3. **Simulation model**

3.1. **Bidirectional Water Transfer System model**

Flowmaster model is shown in Figure 5.

1 is Reservoir 1. 20 is Reservior 2. 2, 3, and 13 are valves of water circuit. 4 is a Four-Way Valve composite component. 16 and 17 are valves of air circuit. 5~11 are the piping components of the water circuit, 14 and 15 are the piping components of the air circuit; 12 is the hydraulic pumps; 18 and 19 are the pressure source components of the air circuit. 21~23 and 26 are the elbows; 24, 25, 27, 28, 29, 32, 33 are valve opening controllers.
3.2. Valve opening curve

The simulation uses three different valve opening curves, which are the linear (Figure 6(a)), the stepped (Figure 6(b)) and the stepped curve (Figure 6(c)).

The change process is state 1, state 2, and state 3. C27, C28, and C29 are the control components of the Four-Way Valve, and C24, C25 are the gas valve control components. The gas valve closes and opens quickly, and the two stop valves are open. The degree is always 1.
3.3. Calculation mode
Adjust the calculation mode to compressible transient, with a time step of 0.1s and a total time of 16s

4. Simulation result analysis

4.1. Flow rate of reservoir
Flow rate of reservoir 1 under different valve opening curves is shown in Figure 7, where the blue line is the gas flow rate and the red line is the water flow rate. Generally, in the transition process between state one and state two, water flow into Reservoir 1 and gas flow out of Reservoir 1; in the transition process between state two and state three, water flow out of Reservoir 1, and gas flow into Reservoir 1.

For the linear opening curve, the flow rate changes smoothly because the valve opens slowly. During 6-8s, although it did not enter state three, there is still some water flowing out of Reservoir 1, and during 7-8s, gas began to flow into Reservoir 1.

For the stepped and the stepped curve opening curves, although there is a case of water flowing out of Reservoir 1 a short time before 6s, both the outflow flow rate and the outflow time length are far less than the linear. And the gas at this time has been maintained in an outflow state. The valve opening changes of the other two opening curves are more rapid, so the transition curve is steeper, while the stepped curve is smoother than the stepped curve at the four moments of state transition, that is 4s, 6s, 10s, and 12s.
4.2. Flow rate of hydraulic pump

(a) Linear

(b) Stepped

(c) Stepped curve

Figure 8: Flow rate of hydraulic pump
Hydraulic pump flow rate under different valve opening curves is shown in Figure 8. Generally, in states 1, 2, and 3, hydraulic pump flow rate is respectively about 1510 m$^3$/h, 1750 m$^3$/h and 1590 m$^3$/h. Hydraulic pump flow rate of the stepped and the stepped curve decreases slowly in state 1 and state 3, while flow rate remains unchanged in the state two. When entering state 3 at 12s, the hydraulic pump flow rate of the two valve opening curves changes suddenly, increasing to 1600 m$^3$/h in a short time. But that of the stepped curve is smoother and more gentle.

4.3. Pressure front and back hydraulic pump

(a) Linear

(b) Stepped
Fig. 9 shows the curve of pressure front and back the hydraulic pump under different valve opening curves. With the valve opening degree changing, the trend of decreasing firstly and then increasing show up. That is, the head of the hydraulic pump also firstly decreases and then increases. It reaches the minimum when the linear opening curve at 8s, the stepped and the stepped curve in 6-12s. Only at 0s and 16s there is pressure jump in the linear opening curve, which has a great impact on the system.

For the stepped opening curve and the stepped curve opening curve, in 6s-10s, namely state two, there is negative pressure front and back the hydraulic pump, and there are large pressure fluctuations. Because of no voltage components such as pressure source in the circuit, there is a drastic transition process. However, at 4s and 12s, compared with the stepped opening curve, the pressure of the stepped curve has no sudden change, and the transition process is smoother. There is only a small pressure fluctuation phenomenon front and back 12s.

4.4. Pressure around Four-Way Valve
Pressure around Four-Way Valve under different valve opening curves are shown in Figure 10. Node 8 (connected to port D) is connected to Reservoir 1, node 9 (connected to port A), and node 10 (connected to port B) are connected to the hydraulic pump, and the node 11 (connected to the port C) is connected to Reservior 2.

Node 8 (green line) and node 11 (red line) have a sudden pressure change at 8s, that is state 2, when in the linear opening curve.

When in the stepped opening curve, pressure at node 8 when in state 2 (green line) decreases slightly, corresponding to the exhaust process in the Reservior 1, and the pressure drop in the reservoir 1 simultaneously induces the pressure at the node 8 decreasing. Because of the pressure fluctuations of the hydraulic pump, node 9 (blue line) and node 10 (red line) also have large pressure fluctuations, and there is obvious negative pressure.

Similarly, for the stepped curve opening curve, there is no sudden pressure change at 4s and 12s, and node 8 (green line) and node 11 (brown line) also have no sudden pressure change at 6s and 10s. Although there still remains small pressure fluctuation, but compared to the stepped opening curve, the stepped curve transits better.
5. Concluding
Establishing the simulation model of Bidirectional Water Transfer System, this paper designs three different valve opening curves: the linear, the stepped and the stepped curve opening curve, and simulates the transient system characteristics of the Bidirectional Water Transfer System under different curves, which may help further study on the influence of valve to pipeline system. This paper draws the concluding that:

- The linear opening curve has a large pressure mutation at the beginning and end of the state transition, which has a great impact on the Bidirectional Water Transfer System. Compared with the linear opening curve, the stepped opening curve has a smaller pressure mutation when the stepped curve opening curve only has small pressure fluctuation instead of pressure change, while compared with the linear opening curve.
- The stepped and the stepped curve opening curve can effectively avoid the phenomenon of gas flowing into the Reservior 1 before state 2, and they can greatly improve the phenomenon of water flowing out of the Reservior 1 before state 2.
- Extending valve opening time can smooth the flow and pressure changes in the transition process, but it cannot eliminate the mutation at the beginning and end of the state.

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