Analysis on water hammer protection of FPSO ballast water system

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Abstract. In practical engineering, the protection of FPSO water hammer is very important. Through simulation analysis, the relevant data are obtained to provide reference for relevant engineering practice. A general-purpose FPSO ballast water pipe network system was established by aft impulse software, and water hammer simulation calculation and analysis were carried out to find out the maximum pressure position of water hammer phenomenon. According to the water hammer generation mechanism, the simulation research was carried out by two-stage valve closing and adding surge tank into the pipeline. It was found that water hammer was easily caused by quick closing valve; the protection method of two-stage valve closing and installation of surge tank has a very objective protective effect, which provides a reference for related projects.

1. Introduction
Ballast water system is a pipeline system with many connectors and equipment in FPSO pipe network system, and its water hammer analysis is very important; in practical engineering, water hammer phenomenon is very easy to damage the pipeline, affect the stability of system operation and cause huge economic losses [1]. Therefore, it is necessary to analyze the system pipeline and calculate its water hammer phenomenon [2]. The selected ballast water pipeline system is calculated by the special water hammer analysis software aft impulse. The phenomenon of water hammer in the pipeline system is reflected through many simulations, and the causes of water hammer pressure are reasonably analyzed. The working conditions of water hammer are optimized through the two-stage closure of valves and the
optimization of surge tank, so as to improve the safety performance of pipeline system operation and provide basis and reference for the normal work of the project.

Aft impulse software can conduct steady-state and transient analysis of incompressible fluid and calculate the transient pressure and water hammer size caused by water hammer in pipe network system [3]. The software can complete the modeling of water conveyance system by dragging; in addition, when the modeling is wrong, it can be deleted and reestablished directly, which has no impact on the system simulation analysis [4]. Software is one of the mainstream application software of water hammer analysis. It is mainly used to calculate and analyze the changes of liquid fluid water hammer and sudden increase of pressure.

2. water hammer calculation equation
The calculation methods of water hammer mainly include graphic method, analytical method and characteristic line method [5]. With the progress of computer technology, the electrical algorithm of characteristic method has also made great progress, and has gradually become the mainstream method of water hammer calculation. Water hammer is embodied in the form of unsteady flow, and the basic differential equation of water hammer is composed of motion equation and continuity equation [6]. The characteristic line method is usually used for numerical calculation of water hammer, which is combined with the corresponding initial conditions and boundary conditions to solve the basic differential equation of water hammer [7].

The derivation of the basic differential equation of water hammer is based on the following three assumptions [8]:

1. The flow is a one-dimensional flow with uniform velocity distribution and the same density at each point of the fluid;
2. Whenever the pipe is filled with continuous fluid, the fracture of water column is not included;
3. The same frictional resistance as that of steady flow is used in transient flow.

According to relevant assumptions, two equations can be used to represent the basic differential equation of water hammer:

Equation of motion

$$\frac{\partial H}{\partial x} + \frac{1}{g} \frac{\partial V}{\partial t} + \frac{V}{g} \frac{\partial V}{\partial x} + f \frac{V}{2g} = 0 \quad (1)$$

Continuous equation

$$\frac{\partial H}{\partial t} + V \left( \frac{\partial H}{\partial x} + \sin \alpha \right) + \frac{a^2}{g} \frac{\partial V}{\partial x} = 0 \quad (2)$$

3. Stress analysis of valve closing water hammer in FPSO pipe network system

3.1. Model construction and pressure check conditions
According to the corresponding drawings of the ballast water system, the aft impulse model is established. The pipeline system selected in the ballast water system is shown in Figure 1.
The pipeline material of the pipe network system is FRP. The Poisson's ratio is about 0.2, and the absolute roughness is 0.00053 cm; the liquid surface pressure of the container is 1 atm and the liquid surface elevation is 8.56 m; the pump flow is set to 1500 m$^3$/h. At this time, the corresponding head is 45 m and the pump speed is 1402 rpm. The pump head curve is shown in Figure 2.

According to the current American Standard ASME b31.3-2012 [9] - [11], the verification of water hammer pressure design needs to meet that the maximum pressure in the pipeline cannot exceed 1.33 times the design bearing pressure of the pipeline system, and the design pressure of the ballast water system is 0.85 mpa, so the maximum allowable water hammer pressure in the pipeline system is 1.1305 mpa.

3.2. Steady state analysis
In the steady-state analysis of the model, aft impulse adopts the solution method of Newton Raphson method basic equation [12].
As shown in Figure 3, under steady-state conditions, water hammer analysis is carried out on the model. After several simulation analysis, it is found that the maximum static pressure value in each pipeline is 0.478 mpa, while 0.478 mpa is less than the maximum allowable water hammer pressure value in the pipeline system of 1.131 mpa. Therefore, under steady-state conditions, the model runs smoothly and meets the design principles of FPSO ballast water system.

3.3. Transient analysis of valve closing water hammer

According to the actual engineering situation, the valve opening and closing time will increase with the increase of valve size [13]. In the case of transient simulation, each working condition shall be divided according to the standard of valve switching time. Therefore, the relationship between valve size and valve switching time shall be known, as shown in Table 1.

| Valve size (inch) | Reasonable operation time (s) | Valve size (inch) | Reasonable operation time (s) |
|------------------|-----------------------------|------------------|-----------------------------|
| 5                | 5—15                        | 22               | 22—66                       |
| 6                | 6—18                        | 24               | 24—72                       |
| 8                | 8—24                        | 26               | 26—78                       |
| 10               | 10—30                       | 28               | 28—84                       |
| 12               | 12—36                       | 30               | 30—90                       |
| 14               | 14—42                       | 32               | 32—96                       |
| 16               | 16—48                       | 34               | 34—102                      |
| 18               | 18—54                       | 36               | 36—108                      |
| 20               | 20—60                       | 40               | 40—120                      |
|                  | >40                         |                  | >120                        |

According to the queried valve technical manual, the calculation formula of valve flow coefficient CV is as follows:
\[ C_v = \frac{29.9 d_L^2}{2.54^2 \sqrt{R}} \]  

(3)

Calculate the required valve CV value according to the formula, as shown in Table 2.

| Valve size (inch) | CV value |
|------------------|----------|
| 16               | 12622    |
| 18               | 15644    |
| 20               | 19672    |

When the CV value of the valve in the pipeline and the valve closing time are determined, the valve closing water hammer of the pipeline can be studied. The valve closing conditions of the selected ballast water pipeline system are shown in Table 3.

| Working condition number | Working condition analysis          |
|--------------------------|------------------------------------|
| 1                        | The 16inch valve is closed separately |
| 2                        | The 18inch valve is closed separately |
| 3                        | The 20inch valve is closed separately |

Analysis of working condition 1: for a 16 inch valve, the valve closing time is 16 to 48 seconds according to the selected value in Table 1, and the initial valve closing time is set to 16 seconds. The pressure value of each pipeline is shown in Figure 4, and the valve closing curve is shown in Figure 5:

![Figure 4](image_url)  

Figure 4 pressure value of each pipeline after 16inch valve is closed for 16S
According to the analysis results, when the 16 inch valve is closed in a straight line for 16 seconds, the maximum water hammer pressure in the ballast water system occurs on pipeline 5. At 16.01 seconds, it is about 0.846 mpa, which is less than the maximum allowable water hammer pressure in the pipeline system of 1.131 mpa. Generally, there will be no water hammer to damage the pipeline, meeting the design principles of FPSO ballast water system.

Analysis of working condition 2: for the 18 inch valve, the valve closing time is within 18 to 54 seconds according to the selected value in Table 1, and the initial valve closing time is set to 18 seconds for analysis, as shown in Figure 6.

According to the analysis results, when the 18 inch valve is closed in a straight line in 18 seconds, the maximum water hammer pressure in the ballast water system also occurs in pipeline 5. When it occurs in 19.70 seconds, it is about 3.059 MPa, which is greater than the maximum allowable water hammer pressure in the pipeline system of 1.131 MPa. It is very easy to produce water hammer, which needs to be optimized.

Condition 3 Analysis: for 20 inch valves, the valve closing time is within 20 to 60 seconds selected in Table 1, and the initial valve closing time is set to 20 seconds for analysis. Since there are five 20 inch valves in the pipeline, it is necessary to analyze the situation of 20 inch valves, as shown in Table 4.
Table 4  water hammer pressure corresponding to 20Inch valve

| number | Corresponding condition of 20 inch valve | Maximum water hammer pressure generating line | Maximum water hammer pressure (MPA) |
|--------|---------------------------------------|---------------------------------------------|-------------------------------------|
| 1      | Valve closed one                       | Line 5                                      | 1.565                               |
| 2      | The valve closes two                    | Line 5                                      | 1.390                               |
| 3      | The valve closes three times            | Line 33                                     | 1.952                               |
| 4      | The valve closes four                   | Line 23                                     | 1.845                               |
| 5      | All valves are closed                   | Line 29                                     | 1.358                               |

4. Analysis on water hammer protection of valve closing

4.1. Two stage valve closing water hammer protection

Two stage valve closing protection treatment shall be carried out for working conditions (working conditions 2 and 3) in the ballast water system.

The optimization analysis of "two-stage valve closing" is carried out for condition 2: for the 18 inch valve, the initial valve closing time is set as 18 seconds, but the analysis of "two-stage valve closing" is fast closing 80 °, slow closing 20 °, fast closing 90 °, slow closing 10 °, and the CV value of 18 inch valve is 15644, the corresponding service time and CV value of the two stages under this closing condition are shown in Table 5 and table 6.

| Valve closing stage | Final time | CV value |
|---------------------|------------|----------|
| Quick closing valve | 4          | 3129     |
| Close the valve slowly | 18      | 0        |

| Valve closing stage | Final time | CV value |
|---------------------|------------|----------|
| Quick closing valve | 2          | 1564     |
| Close the valve slowly | 18      | 0        |
Figure 7 corresponding curve of two-stage valve closing and quick closing 80° and 90° valves of 18 inch valve

After several simulation analysis, the maximum water hammer pressure under two-stage valve closing and the water hammer pressure of straight-line valve closing in the previous 18 seconds are shown in Table 7.

Table 7 Comparison of maximum water hammer pressure between two stages and linear valve closing

| Valve closing mode                                      | Maximum water hammer pressure (MPA) |
|---------------------------------------------------------|-------------------------------------|
| 18Second linear valve closing                           | 3.059                               |
| 18Second two-stage valve closing, fast closing 80°, slow closing 20° | 1.264                               |
| 18Second two-stage valve closing, fast closing 90°, slow closing 10° | 0.969                               |

According to the analysis, when the valve is closed in a straight line for 18 seconds, the maximum water hammer pressure is 3.059 mpa, which is far greater than the maximum allowable water hammer pressure of the ballast water system of 1.131 mpa. When the valve is closed in two stages through the slow closing butterfly valve, the maximum water hammer pressure in the pipeline is 1.264 mpa when the rapid closing is 80° and the slow closing is 20° in the preliminary design, although it is still greater than the maximum allowable water hammer pressure in the pipeline, it has obvious optimization effect compared with the straight-line valve closing in 18 seconds. At this time, continue to set the slow closing butterfly valve so that its fast closing is 90° and slow closing is 10°. Under this optimization condition, the maximum water hammer pressure in the pipeline is 0.969 mpa, which is less than the maximum allowable water hammer pressure of the ballast water system and meets the design requirements.

The "two-stage valve closing" analysis was carried out for condition 3. The initial valve closing time of the 20 inch valve remained unchanged, and the valve was closed for 20 seconds. The valve was closed quickly for 80° and then slowly for 20°, and the CV value of the 20 inch valve was 19672. Under this closing condition, the corresponding service time and CV value of the two stages are shown in Table 8.
Table 8  fast closing 80 ° and slow closing 20 ° of 20 inch valve

| Valve closing stage | Final time | CV value |
|---------------------|------------|----------|
| Quick closing valve | 4          | 3934     |
| Close the valve slowly | 20        | 0        |

Figure 8  80 ° curve of two-stage valve closing and quick closing of 20 inch valve

The maximum water hammer pressure of "two-stage valve closing" of 20 inch valve and the previous water hammer pressure of "straight-line valve closing" are shown in Table 9.

Table 9  maximum water hammer pressure of two-stage valve closing of 20 inch valve

| number | Corresponding condition of 20 inch valve | 20 Maximum water hammer pressure of second linear valve closing (MPA) | Maximum water hammer pressure of two-stage valve closing (MPA) |
|--------|-----------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------|
| 1      | Valve closed one                         | 1.565                                                               | 0.972                                                         |
| 2      | The valve closes two                     | 1.390                                                               | 0.884                                                         |
| 3      | The valve closes three times             | 1.952                                                               | 0.862                                                         |
| 4      | The valve closes four                    | 1.845                                                               | 0.850                                                         |
| 5      | All valves are closed                    | 1.358                                                               | 0.845                                                         |

4.2. Surge tank water hammer protection

The optimization analysis and treatment of surge tank are carried out for working conditions (working conditions 2 and 3) in ballast water system.

According to the optimization analysis of the pressure regulating tower under condition 2, the initial closing time of the 18 inch valve is set to 18 seconds, and the pressure regulating tower is added to the valve closing pipeline, as shown in Figure 9.
Figure 9  adding surge tank in front of 18 inch valve

Table 10 shows the comparison between the maximum pressure in the pipeline and the previous 18 inch valve closing within 18 seconds

| Closing mode       | Maximum water hammer pressure (MPA) |
|--------------------|-------------------------------------|
| 18Second closing   | 3.059                               |
| Add surge tank     | 0.799                               |

Through the analysis of the model, it is found that when the surge tank is added to the pipeline, the maximum water hammer pressure in the pipeline is reduced from 3.059 mpa to 0.799 mpa, which is less than the maximum allowable water hammer pressure of the ballast system of 1.131 mpa, meeting the design requirements.

Optimize the pressure regulating tower under condition 3. Install the pressure regulating tower behind the 20 inch valve, as shown in Figure 10. The analysis results are as follows.

Figure 10  installation of pressure regulating tower behind valve

(1) When only one 20 inch valve is closed, the maximum water hammer pressure is optimized through the surge tank.

Figure 11  optimized maximum water hammer pressure of surge tank
The simulation analysis shows that when only one 20 inch valve is closed, the maximum water hammer pressure is reduced from 1.565 mpa to 1.366 mpa. Although it is still greater than the maximum allowable water hammer pressure of the pipeline of the ballast water system of 1.131 mpa, the maximum water hammer pressure in the pipeline has been optimized to a certain extent, subsequently, the pressure regulating tower can be added where the pipeline pressure is greater than the maximum allowable water hammer pressure, as shown in Figure 12.

The analysis shows that when the surge tank is added behind the 20 inch valve and the pipeline pressure is greater than the maximum allowable water hammer pressure, the water hammer pressure in the pipeline reaches the optimal effect of 0.924 mpa, which meets the design principle of FPSO ballast water system.

(2) If this method is used to close two 20 inch valves until they are all closed, the maximum pressure of pipeline water hammer in subsequent analysis is shown in Table 11.

| number | 20 inch valve closed | 20 Maximum water hammer pressure of second closing valve (MPA) | Maximum water hammer pressure after optimization of surge tank (MPA) |
|--------|----------------------|-------------------------------------------------------------|-------------------------------------------------|
| 1      | The valve closes two  | 1.390                                                       | 0.957                                           |
| 2      | The valve closes three times | 1.952                                                      | 0.883                                           |
| 3      | The valve closes four   | 1.845                                                       | 0.852                                           |
5. Conclusion
In this paper, the professional water hammer transient analysis software AFT Impulse is used to model the FPSO ballast water pipe network system. By analyzing the water hammer pressure of FPSO ballast water pipe network system under steady-state and transient conditions, and optimizing and analyzing the water hammer protection methods such as two-stage valve closing and Surge Tower method for the conditions that do not meet the design requirements, the following conclusions are drawn:

(1) The system operates stably under steady-state conditions, generally meeting the design principles of FPSO ballast water system; when the valve is closed quickly, a certain water hammer effect will occur in the ballast water system, which needs to be optimized;

(2) The water hammer protection method of two-stage valve closing has good protection effect, which can greatly reduce the maximum water hammer pressure in the pipeline and improve the engineering efficiency under the condition of the same total valve closing time.

(3) The surge tank has an obvious effect on reducing the water hammer pressure value of the pipeline, and the effect is better after being installed in the pipeline of the ballast water system than in front of the valve. It can greatly reduce the maximum water hammer pressure value in the pipeline and improve the engineering efficiency under the condition of the same total valve closing time, but the use cost is relatively high.

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