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Article

Design and Experiment-Based Optimization of High-Flow Hydraulic One-Way Valves

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Abstract: High-flow hydraulic one-way valves in water pipes are typically used to mitigate conditions, which would otherwise cause vibration and cavitation erosion after long-term operation. To prevent cavitation and enhance the performance of hydraulic one-way valves, in the present work a dedicated experimental study has been conducted. The structural parameters relating to the pilot valve core, the main valve core, and the through-flow section of the considered flow channel have been changed to analyse reverse impact, and cavitation, characteristics. The results show that the control pressure has a weak effect on the cavitation characteristics, while changes in the structural parameters can significantly affect them. In particular, the cavitation index, representing the extent of cavitation, has been found to display a linear correlation with the inlet pressure, but, not with the inlet flow rate. Most importantly, a stepped throttling structure can reduce the pressure oscillation, improve the response speed, enhance the impact characteristics, and decrease the likelihood and severity of cavitation. The larger the flow passage area, the shorter the unloading time. Cavitation mainly occurs when the pilot valve core is fully opened. The stepped main valve core throttling structure has been found to be an optimal option.

Keywords: High-flow; structural design; impact; cavitation

1 Introduction

The use of water is ubiquitous [1–3]: more attention has been paid to the water as a medium for hydraulic transmission, and some important problems related have been investigated [4–7]. Theoretical methods and applications of water-based hydraulic components [8–11] have been widely proposed. The maximum working pressure of a water-medium hydraulic control valve has reached 32 MPa [12]. The hydraulic one-way valve is the most commonly used in such systems.

As a result of the hydraulic one-way valve often operating at pressures greater than 30 MPa and flowrates of 1000 L/min, there are some problems to be overcome such as: intense pressure undulations, cavitation, and so on [13–15], however, the impact and cavitation characteristics under high-pressure high-flow conditions in the reverse direction have been seldom reported [16].

In this study, the structural parameters of a pilot valve core, main valve core, and through-flow section of flow channels are designed to explore reverse impact and cavitation characteristics. In addition, the matching of structural parameters is optimized. The optimized high-flow hydraulic one-way valve shows the following significant advantages: cavitation reduction, high reliability, longer service-life, and performance improvements.

2 Unloading Form and Structural Parameters Design

Fig. 1 demonstrates a schematic diagram of water-medium high-flow hydraulic one-way valve consisting of a pilot valve core, the main valve core, piston, and other components.

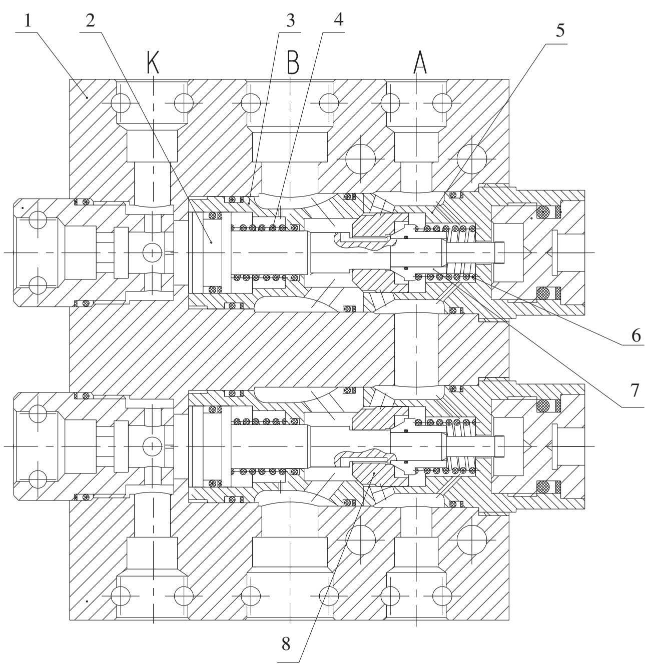

Figure 1: Schematic diagram of water-medium high-flow hydraulic one-way valve. 1. Valve body, 2. Piston, 3. Valve seat, 4. Return spring, 5. Valve sleeve, 6. Valve core return spring, 7. Pilot valve core and 8. Main valve core

The opening states of the valves are shown in Figs. 2 and 3 (red dotted lines therein indicate the flow of water).

Fig. 2 shows that when the pilot valve core is opened, the main valve core does not move, high-pressure water is discharged through the gap between the main valve core and the pilot valve core, permitting pressure unloading. As shown in Fig. 3, after the main valve core is opened, besides the gap in Fig. 2, the water also overflows through the gap between the valve seat and the main valve core, permitting flow unloading.

A pilot valve core with a 45° cone angle is designed, moreover, pilot valve cores with different cone angles of 30° and 60° are analyzed for comparative purposes (Fig. 4).

In order to enhance the dynamic characteristics and reduce cavitation, a multi-stage throttle structure is adopted and three kinds of main valve cores are designed (Fig. 5). Type *I* is a stepped three-step throttle structure with a buffer groove; Type *II* is a stepped three-step throttle structure; Type *III* is an abrupt type throttle structure. In theory, the more numerous throttle structures contribute to vibration reduction, however, it is difficult to achieve this requirement in practice.

When only the pilot valve core is opened, the flow passage area is equivalent to the through-flow section between the main valve core and the pilot valve core, and depends on the cross-sectional area of keyways in the valve rod. Three keyways with total flow passage areas of 21.6, 31.2, and 36 mm^2 are designed (Fig. 6).

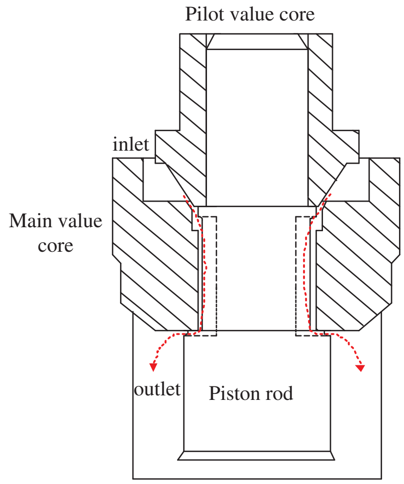

Figure 2: Pilot valve core opened

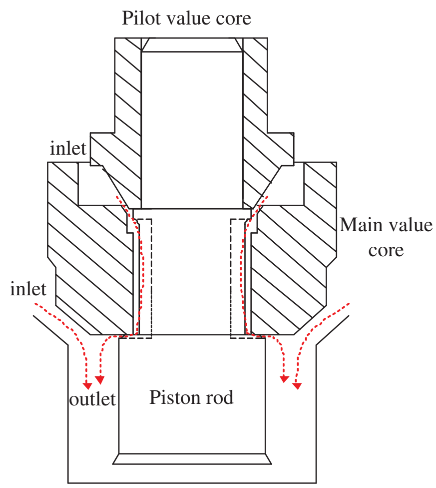

Figure 3: Main valve core opened

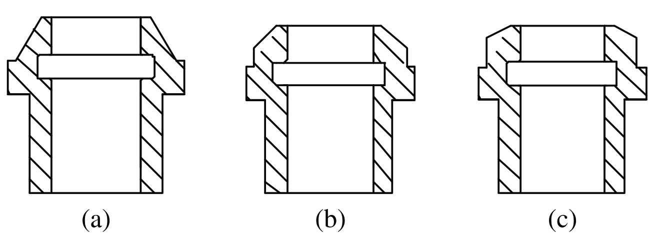

Figure 4: Pilot valve core for different cone angles. (a) 30°, (b) 45° and (c) 60°

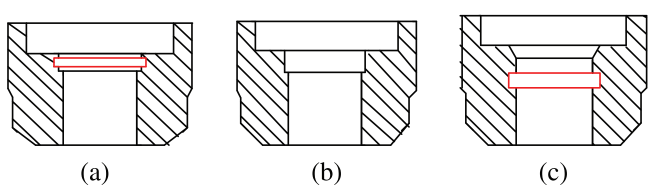

Figure 5: Different main valve cores. (a) Main valve core *I*, (b) Main valve core *II* and (c) Main valve core *III*

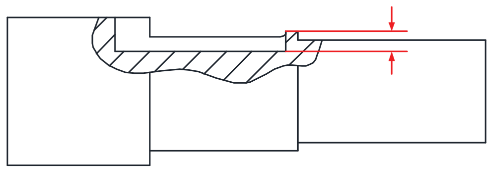

Figure 6: Through-flow keyway on the valve stem

3 Experimental Work

3.1 Experimental System

The schematic diagram of experimental system is illustrated in Fig. 7.

Firstly, the right of the pressurized cylinder is filled with water through the water pump station, the pressurized cylinder piston is pushed to the left. Secondly, the accumulator is charged to the pre-set pressure. Then, the cartridge valve is opened, the oil in accumulator is released rapidly, causing a high-pressure high-flow of water in the right of the pressurized cylinder.

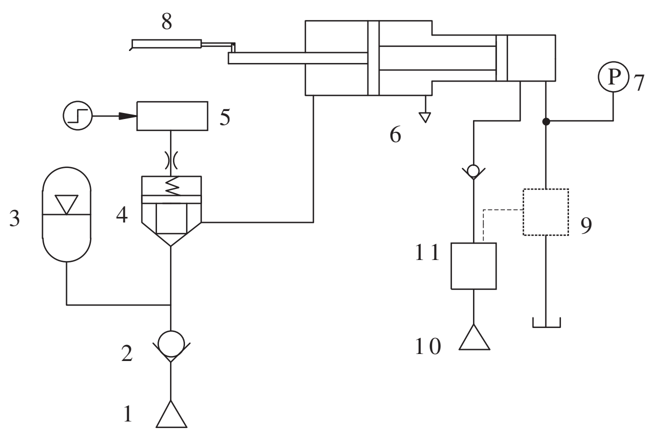

Figure 7: Diagram showing the test system. 1. Oil source, 2. One-way valve, 3. Accumulator, 4. Cartridge valves, 5. Pilot valve, 6. Pressure cylinder, 7. Pressure sensor, 8. Displacement sensors, 9. Hydraulic one-way valve, 10. Water pump station and 11. Directional valve

3.2 The Impact Characteristics

3.2.1 Influence of Control Pressure

Under a pressure of 30 MPa, the performance of the hydraulic one-way valve is s shown in Fig. 8. When the control pressures are 12 MPa, 14 MPa, and 16 MPa, the unloading times are 0.84 s, 0.65 s, and 0.60 s: it can be seen that, as the control pressure increases, the unloading time is significantly reduced.

In addition, when the hydraulic one-way valve is opened, pressure undulations are formed thus generating an inlet pressure. The conversion between kinetic energy and pressure energy proceeds continuously, thus destroying the balance between the piston and valve core. Therefore, the valve core is closed, and then the impact is generated. Under an increased control pressure, the maximum pressure decreases from 31.4 MPa to 30.1 MPa, and the undulation time decreases from 0.25 s to 0.17 s. With the acceleration of the unloading process, the flow gradient increases and the undulations diminishes.

Under the greater control pressure, the ability to avoid the force imbalance between the valve core and the valve stem is stronger. In this way, the response speed is improved and the pressure impact is decreased and the stability of the hydraulic one-way valve is enhanced.

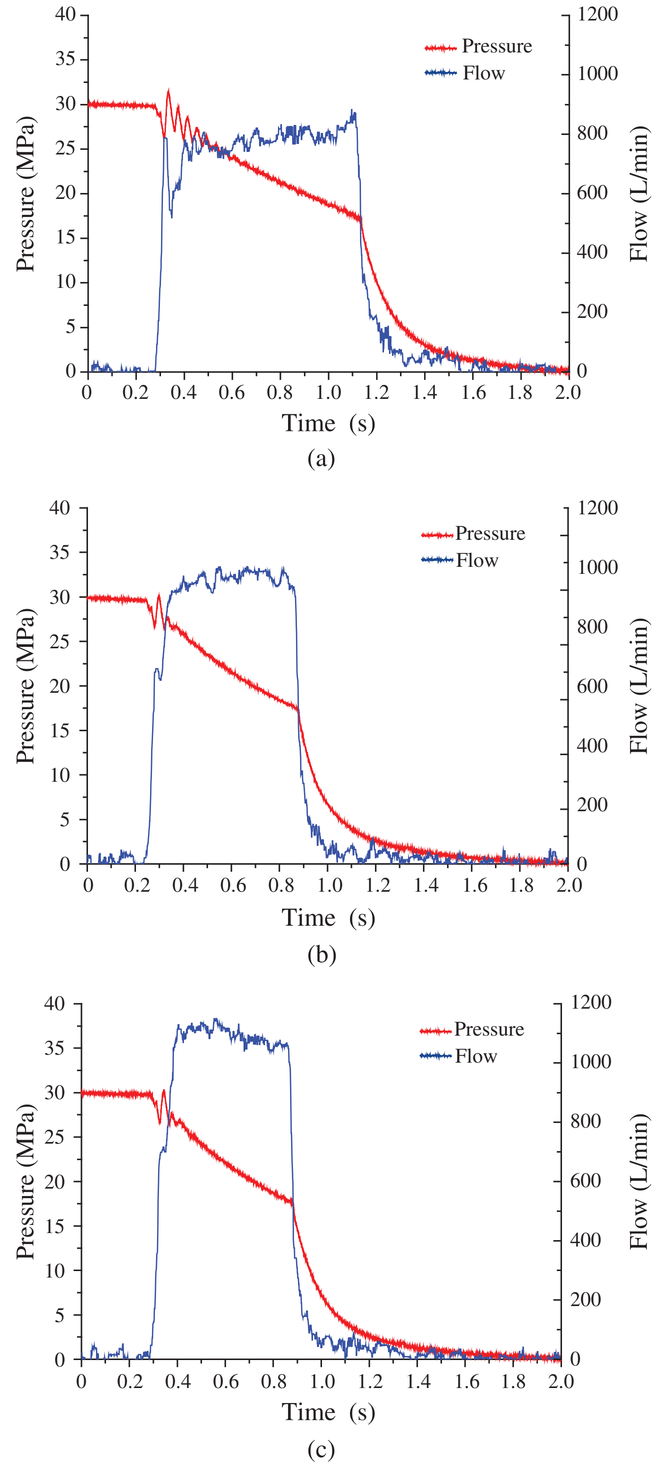

Figure 8: Impact characteristics for different control pressures. (a) 12 MPa, (b) 14 MPa and (c) 16 MPa

3.2.2 Influence of the Pilot Valve Core

The inlet pressure and the control pressure are set to 30 MPa and 14 MPa respectively. The pressure and flow for different pilot valve cores are shown in Fig. 9.

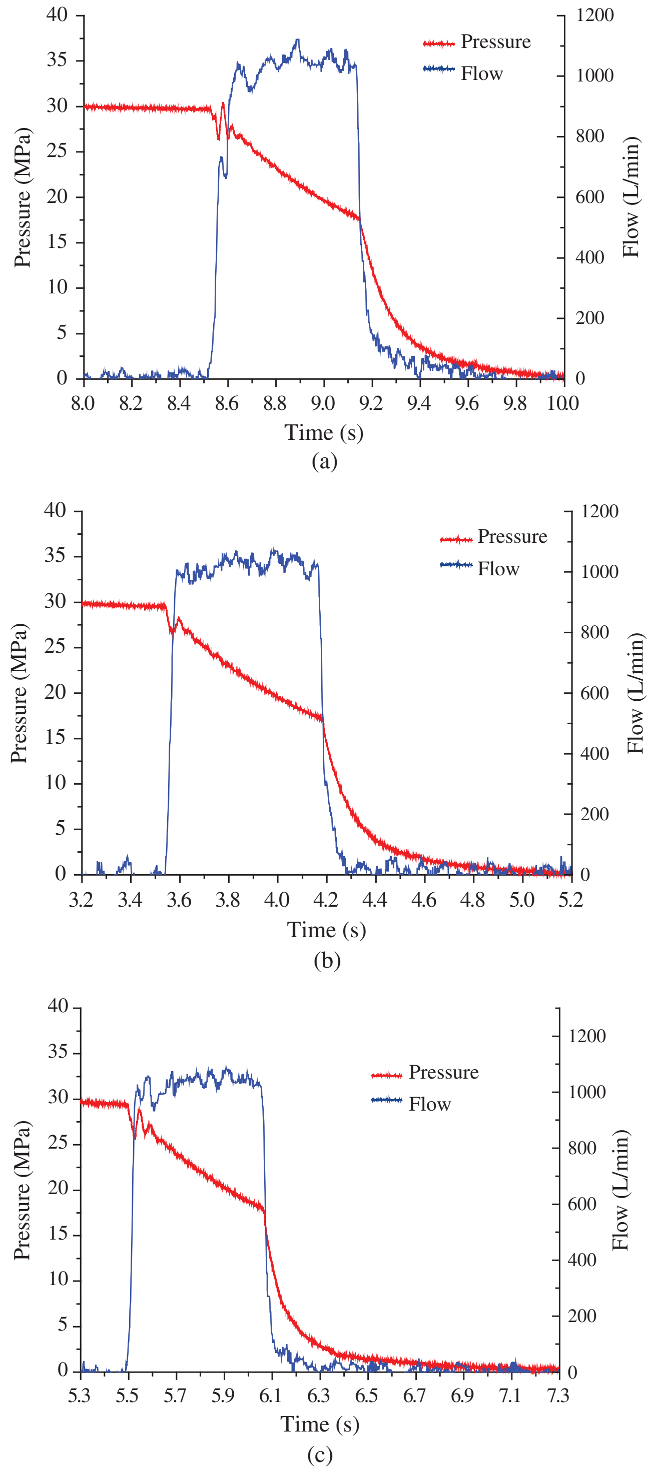

Figure 9: Impact characteristics for different pilot valve cores. (a) 30°, (b) 45° and (c) 60°

The pressure undulation of the 45° pilot valve core is the lowest (Fig. 9b) and the impact unloading moment is more stable than that of the other two valve cores. Flow undulation also always remains at about 1055 L/min and is stable. Dynamic characteristic data are listed in Tab. 1.

Table 1: Dynamic characteristics of different pilot valve cores

Cone angle/°	Peak pressure/MPa	Peak flow/(L/min)	Flow rising gradient/(10^5 L/min^2)	Unloading time/(s)
30	30.38	1094	4.68	0.758
45	26.86	1078	4.90	0.754
60	28.57	1096	6.89	0.701

The larger cone angle of the pilot valve core corresponds to the higher flow gradient, and vibrations thereof are more significantly reduced, however, the peak flows under different cone angles remain similar, therefore, the larger cone angle, the faster the unloading process of the hydraulic one-way valve. The stable unloading process allows an excellent dynamic performance.

3.2.3 Influence of the Main Valve Core

The impact and control pressures are respectively set to 30 MPa and 14 MPa and the pressure-flow-time curves of different main valve cores are illustrated in Fig. 10.

In terms of pressure, the main valve core *I* with the lower undulation peak and shorter unloading time is better than main valve cores *II* and *III*. The influence of the difference in the main valve cores on the flow is significantly greater than that on the pressure. The dynamic characteristic test data pertaining to the different main valve cores are listed in Tab. 2 where "Δ" denotes that a flow gradient value that is out of range.

Under impact conditions, the unloading time of the main valve core *I* is the shortest, the flow gradient is the highest (Tab. 2 and Fig. 10), moreover, the pressure oscillation peak is the smallest. The flows of main valve cores *II* and *III* are always in a rising or oscillating stage without a stable range of operation, so their flow gradients are ignored.

It can be concluded that, in terms of impact characteristics, the stepped multi-stage throttle structure is better than the abrupt type structure. Multi-stage throttle structures can lead to a rapid flow-velocity decline and a pressure rise, whereas the abrupt type of multi-stage throttle structures can result in a flow-velocity recovery, which finally causes large-amplitude oscillations. The stepped structure is characterized by a gradual decrease across the whole flow channel, so the changes in flow and pressure are smooth and stable without undue oscillation.

3.2.4 Influence of Flow Passage Area

It is supposed that the inlet pressure and the control pressure are 30 and 14 MPa, respectively. Under these conditions, the impact characteristics of the high-flow hydraulic one-way valve with different flow passage areas are shown in Fig. 11.

With the increase in the flow passage area, the unloading time decreases from 0.8 s to 0.6 s (Fig. 11), but the fluid pressure fluctuates to a greater extent (Tab. 3).

As the flow passage area increases, the unloading time decreases and the flow increases more rapidly (Fig. 11 and Tab. 3), however, the fluid pressure does not decrease linearly because the pilot valve core is used for pressure relief. In this stage, excessive increase in the flow passage area causes not only pressure relief, but also flow discharge. Therefore, the flow reaches the peak within a short period. Although the structure with a flow passage area of 36 mm^2 allows a faster unloading rate, its peak pressure is beyond its working range. Hence, it is inadvisable to utilize such a structure. When the flow passage area is 31.2 mm^2, the system undergoes an insignificant pressure undulation, has a short relief period, and a moderate flow gradient, therefore, the structure with a flow passage area of 31.2 mm^2 is deemed to be optimal.

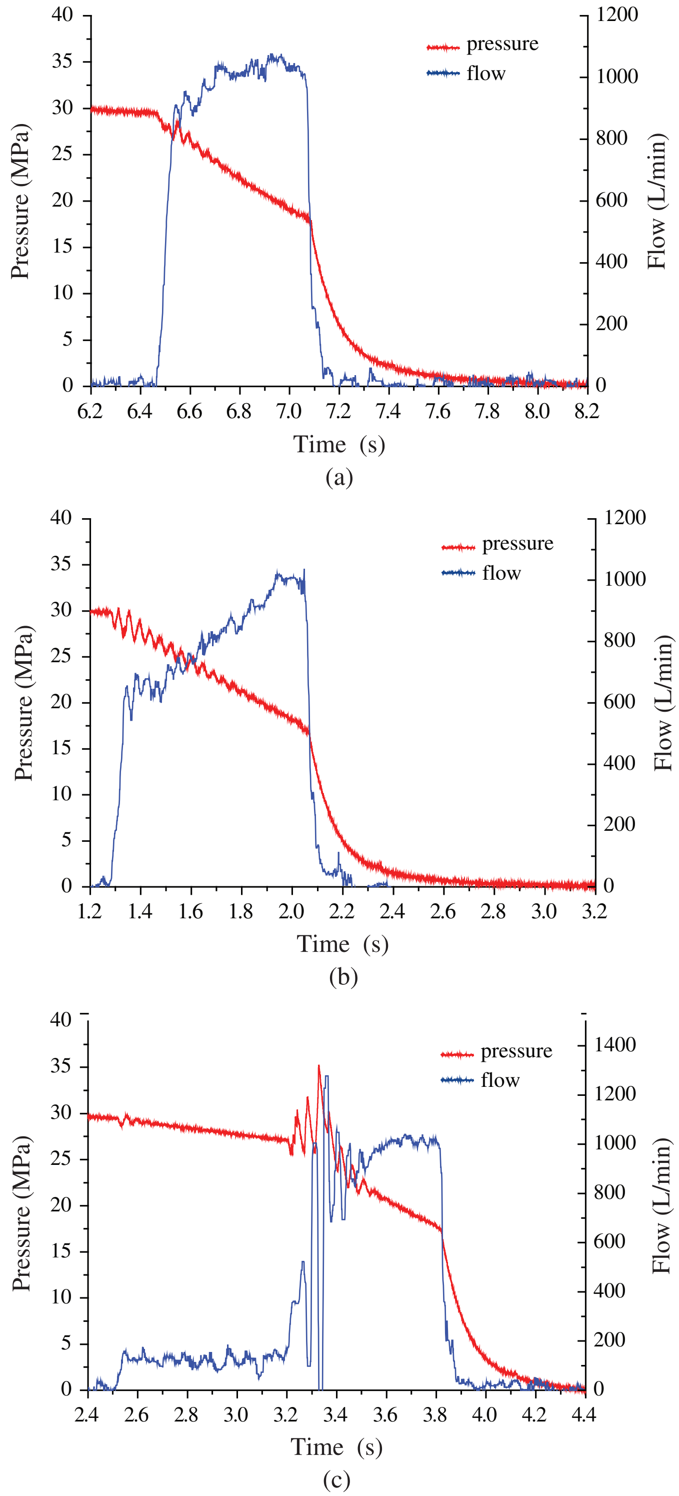

Figure 10: Impact characteristics for different main valve cores. (a) Main valve core *I*. (b) Main valve core *II* and (c) Main valve core *III*

Table 2: Dynamic characteristic testing data of different main valve cores

Valve core no.	Peak pressure/MPa	Peak flow/(L/min)	Flow gradient/(10^5 L/min^2)	Unloading time/ms
I	28.41	1078	4.86	711
II	30.03	1019	Δ	898
III	35.29	1277	Δ	1454

3.3 Cavitation Characteristics

The cavitation index can be used to evaluate the degree of cavitation:

$$T_F = \frac{\sum_{i=1}^{N} f_i^2 S(f_i)}{\sum_{i=1}^{N} S(f_i)} \tag{1}$$

f_i is the frequency of inlet pressure fluctuations, and $S(f_i)$ represents the power spectrum value for the corresponding frequency.

3.3.1 Influence of Control Pressure

The values of T_f for different control pressures are listed in Tab. 4.

The value of T_f at a control pressure for 14 MPa is maximal, and that for 12 MPa is minimal (Tab. 4), which means the T_f has no relationship with the control pressure.

3.3.2 Influence of Loading

At a control pressure of 14 MPa, the values of T_f under different combinations of parameters are displayed in Tab. 5.

In Scenarios 1, 2, and 5 in Tab. 5, when the flows are the same, T_f increases with the inlet pressure. The higher inlet pressure indicates more intense cavitation. Therefore, the higher the value of T_f, the greater the extent of the cavitation. The results indicate that T_f is a rational parameter to use when analyzing cavitation, however, in Scenarios 2, 3, and 4, when the inlet pressure is 25 MPa and the flowrate is 1000 L/min, T_f is 7,983,990, which is less than that at 700 L/min (9,108,181). Therefore, under the same structural conditions, T_f is linearly correlated with the inlet pressure, but its correlation with the flow is not linear. So, the pressure and velocity vary simultaneously, based on Bernoulli's equation, indicating that the occurrence of cavitation is related to pressure and velocity rather than flow. Therefore, in these hydraulic one-way valves, the onset of cavitation depends on the inlet pressure.

3.3.3 Influence of Structural Parameters

The values of T_f for different pilot valve cores are listed in Tab. 6.

Accordingly, the T_f of the pilot valve core at a cone angle of 60° is the highest, showing that the cavitation therein is the most intense (Tab. 6). The value of T_f of the pilot valve core with a cone angle of 45° is the lowest. In terms of the cavitation characteristics, the pilot valve core with a cone angle of 45° is the optimal option. In terms of the impact characteristics, the pilot valve core with a cone angle of 60° is slightly better than that with a cone angle of 45°. In terms of both the cavitation and the impact characteristics, the pilot valve core with a cone angle of 45° is the better option. The T_f values of different main valve cores are displayed in Tab. 7.

The main valve core *III* has the highest T_f and the highest degree of cavitation, followed by the main valve core *I* (Tab. 7). T_f is thus not directly associated with all the parameters pertaining to the impact characteristics, but the results are consistent with the flow field simulation results. Therefore, the T_f value

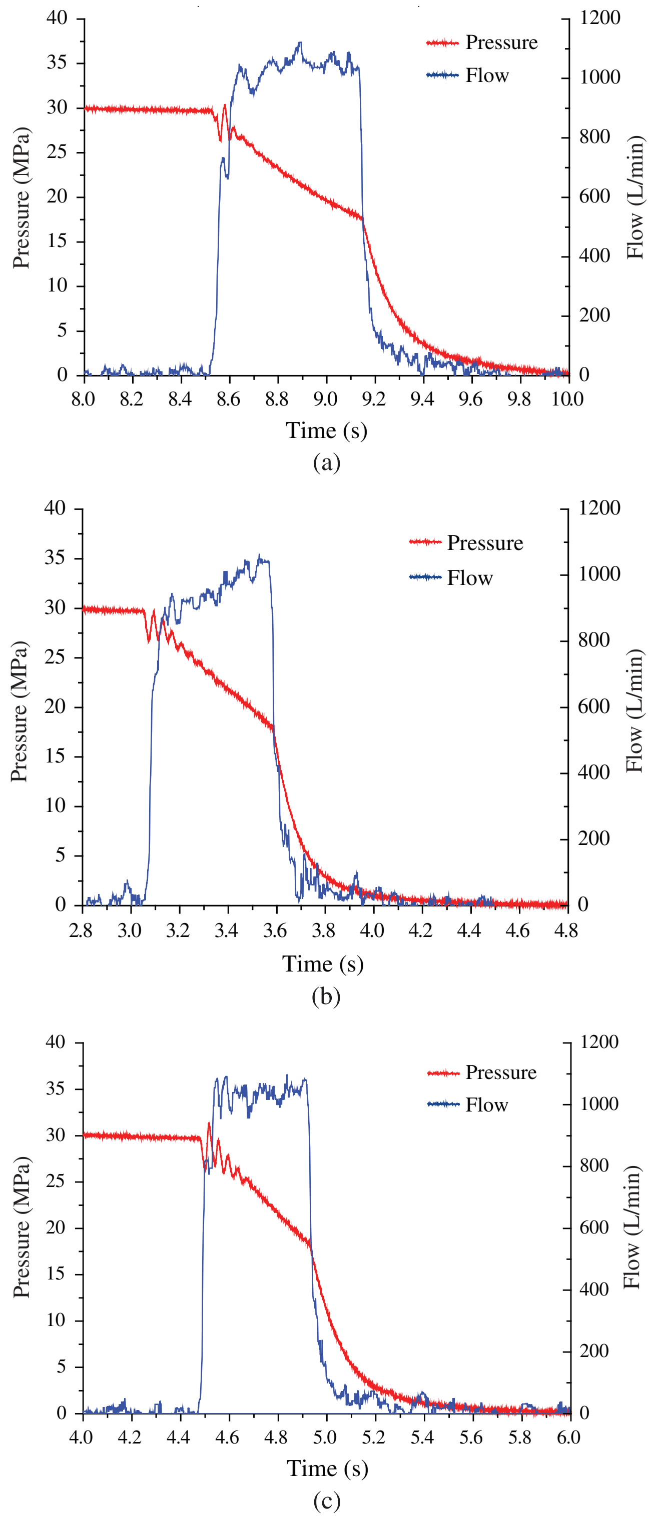

Figure 11: Impact characteristics for different flow passage areas. (a) Flow passage area of 21.6 mm^2, (b) Flow passage area of 31.2 mm^2 and (c) Flow passage area of 36 mm^2

Table 3: Dynamic characteristic test data for different flow passage areas

Flow passage area/ mm^2	Peak pressure/ MPa	Peak flow/ (L/min)	Flow gradient/ (10^5 L/min^2)	Unloading time/ ms
21.6	30.45	1121	4.62	835
31.2	29.79	1065	5.65	696
36	32.39	1098	8.04	620

Table 4: T_f for different control pressures

Control pressure	12 MPa	14 MPa	16 MPa
T_f	6,638,200	8,503,799	8,489,917

Table 5: T_f for different parameters

Scenario	1	2	3	4	5
Parameters	23 MPa, 1000 L/min	25 MPa, 1000 L/min	25 MPa, 500 L/min	25 MPa, 700 L/min	30 MPa, 1000 L/min
T_f	7,388,309	7,983,990	5,360,602	9,108,181	8,963,909

Table 6: T_f values for different pilot valve cores

Cone angle	30°	45°	60°
T_f	8,503,272	7,388,454	10,068,043

Table 7: T_f values for different main valve cores

No.	Valve core *I*	Valve core *II*	Valve core *III*
T_f	9,285,000	8,503,272	9,898,928

of the inlet pressure can reasonably illustrate the degree of cavitation. The cavitation indices of valves with different flow passage areas are listed in Tab. 8.

The larger flow passage area corresponds to the lower values of T_f and less cavitation.

4 Comprehensive Tests for Structural Optimization

Based on the dynamic properties, flow characteristics, and cavitation resistance, the optimal matching of various parts of the valve cores is performed as follows: the pilot valve core with a cone angle of 45°, the main valve core with its three-stage throttle and a buffer vessel at the front end (main valve core *I*), a sealed conical surface, and a flow passage area of 31.2 mm^2 (Fig. 12). The actual assembly is demonstrated in Fig. 13.

Table 8: T_f values for different flow passage areas

Flow passage area/mm^2	21.6	31.2	36
T_f	8,503,272	7,333,571	7,201,949

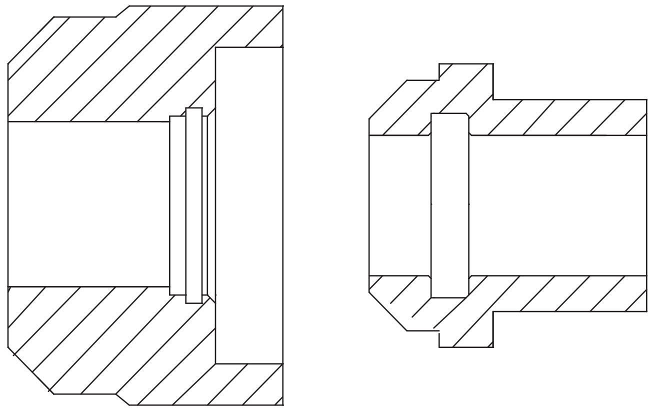

Figure 12: Diagram showing the optimal structure

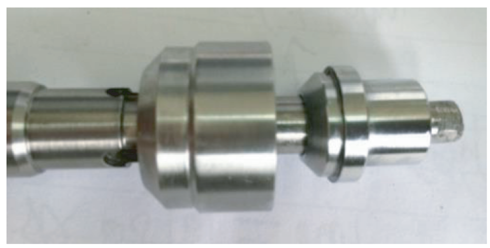

Figure 13: The optimal structure

The impact characteristics of the optimized structure are illustrated in Fig. 14 and the dynamic characteristic parameters of various structures are compared in Tab. 9.

The structural optimization minimizes the undulation in peak pressure (i.e., 28.16 MPa). The parameters of various structures (such as peak flow, flow gradient, and unloading time) are compared (Fig. 14 and Tab. 9). More importantly, the value of T_f (8,564,736) is close to the value of the initial structural parameter of a high-flow hydraulic one-way valve (8,503,272), indicating that the optimized structural matching improves the dynamic characteristics and flow capacity, and restrains the onset of cavitation, thus reducing damage and prolonging the service-life of the valve structure.

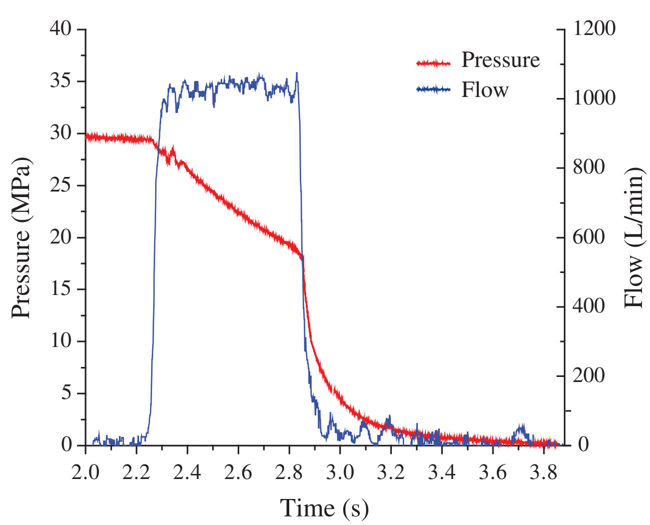

Figure 14: Impact characteristics for optimal structure

Table 9: Characteristic test data pertaining to the optimal structure

	Peak pressure/MPa	Peak flow/ (L/min)	Flow rising gradient/ (10^5 L/min^2)	Unloading time/ms	T_f
Optimal structure (pilot valve core cone angle of 45°, main valve core *I*, flow passage area of 31.2 mm^2)	28.16	1,085	6.21	709	8,564,736

5 Conclusion

In this study, the structural parameters of a pilot valve core, main valve core, and through-flow section of flow channels are designed to explore reverse impact and cavitation characteristics. The results show that the control pressure has little effect on the cavitation characteristics, but structural parameters can significantly affect the impact and cavitation characteristics. The cavitation index represents the extent of cavitation, showing a linear relationship with inlet pressure, but not with inlet flow. Furthermore, the matching of structural parameters is optimized. The optimized high-flow hydraulic one-way valve (with a pilot valve core cone angle of 45°, main valve core *I*, and a flow passage area of 31.2 mm^2) offers the following significant advantages: cavitation reduction, high reliability, longer service-life, and performance improvements.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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