Design and Characteristic Analysis of a New Type of Hydraulic Pulsation Suppressor

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Abstract. In order to decrease the pressure pulsation of high-pressure hydraulic system and speed up the process of high-pressure hydraulic system, a new type of hydraulic pulsation suppressor is designed. The hydraulic pulsation suppressor is designed on the basis of the structural characteristics and attenuation performance of the expansion chamber attenuator and H-type muffler. The theoretical model of the modern hydraulic pulsation suppressor is established based on the fluid theory, and the attenuation performance of the new hydraulic pulsation suppressor is analyzed. The results demonstrate that the designed new hydraulic pulsation suppressor can attenuate the pressure pulsation with a pulsation frequency of 20 Hz ~ 2000 Hz, and attenuate the frequency bandwidth; the attenuation effect is above 50dB, and the attenuation effect is ideal.

1 Introduction

With the development of hydraulic technology, the pressure of the hydraulic system is further increased. High pressure has made the pressure pulsation problem of the hydraulic system more prominent, which has been one of the important factors hindering the development of hydraulic technology. Therefore, reducing the pressure pulsation of the high-pressure hydraulic system is of great importance.

At present, hydraulic pulsation attenuators are mainly used in hydraulic systems to attenuate the pressure pulsations[1-5]. The hydraulic pulsation attenuator installed at the pump outlet mainly includes two types: resonance type and expansion chamber type. OU YANG Xiaoping [6] summarized the resonant hydraulic pulsation attenuator, explained the research progress and performance of various types of resonant hydraulic pulsation attenuators, and proposed that the resonance is best for compactness, high versatility, and strong frequency adaptability. The development trend of the research focusses of hydraulic pulsation attenuator. Resonant hydraulic pulsation attenuators are mainly used to eliminate low-frequency and intermediate-frequency narrow-band pressure pulsations. Wang Yan[7] and others focused on the types, research methods and progress of expansion chamber hydraulic pulsation attenuators, and on this basis, discussed the research trend of expansion chamber hydraulic pulsation attenuators, and proposed that expansion chamber hydraulic pulsation attenuators should be based on theoretical methods and structures. Improve and strengthen research. The attenuation characteristics of the expansion chamber hydraulic pulsation attenuator mainly depend on the expansion ratio and length. This type of hydraulic pulsation attenuator mainly attenuates the pressure pulsation in the high frequency band[8].

Built on the above analysis, a new type of hydraulic pulsation suppressor combining expansion chamber type and resonance type is designed. The original hydraulic pulsation suppressor combines the advantages of the expansion chamber hydraulic pulsation attenuator and the H-type hydraulic silencer. In this study, a theoretical analysis of the latest hydraulic pulsation suppressor was carried out by means of fluid dynamics; the insertion loss was used to evaluate the attenuation performance of the new hydraulic pulsation suppressor. The rationality of the modern hydraulic pulsation suppressor is verified.

2 The working principle of the new hydraulic pulsation suppressor

Figure 1 is a schematic diagram of the structure of the new hydraulic pulsation suppressor. The original hydraulic pulsation suppressor is composed of a rigid shell, two expansion chambers, twelve volume chambers, twelve slender mass chambers and two flow-limiting pipes. When the pulsation of the plunger pump enters the first expansion chamber from the inlet of the suppressor, the pulsation is attenuated for the first time; after the first decay, the pulsation enters the second expansion chamber with different parameters through the first restrictor pipe, and then attenuates again; The second attenuated pulsation flows through the second restrictor pipe and then enters the first volume chamber through the four mass
chambers; the hydraulic oil entering the first volume chamber is divided into two parts, one part is compressed, and the other part enters the first volume chamber. Two volume chambers; the same is valid for the hydraulic oil entering the second volume chamber; at this time, the hydraulic oil entering the third volume chamber is only compressed. The hydraulic oil in the twelve mass chambers moves with the pulsation of the piston, plays the role of liquid sense and fluid resistance, and consumes a part of the pulsation energy at the same time. The expansion chamber, mass chamber, and volume chamber has different parameters, which can be used for multiple frequency ranges. The pressure pulsation is attenuated many times. Through the reasonable design of the modern hydraulic pulsation suppressor, a new type of hydraulic pulsation suppressor integrating expansion chamber, restrictor tube, mass chamber and volume chamber is realized.

The simplified model of the new hydraulic pulsation suppressor is shown in Figure 2. In Figure 2, \( P_1, Q_1 \), and \( P_2, Q_2 \) are the frequency domain dynamic pressure and flow at the inlet and outlet of the new hydraulic pulsation suppressor; \( P_6, Q_6 \), and \( P_{11}, Q_{11} \) are the frequency domain dynamic pressure and flow at the inlet and outlet of node 1; \( P_4, Q_4 \), and \( P_5, Q_5 \) are the frequency domain dynamic pressure and flow at the inlet and outlet of the expansion chamber 1; \( P_{13}, Q_{13} \) are the frequency domain dynamic pressure and flow at the inlet and outlet of the expansion chamber 2.

Figure 3 is an equivalent simplified model diagram of node 1. In Figure 3, \( Q_x \) and \( P_x \) (\( x = 7, 8, 9, 10 \)) are the frequency domain dynamic pressure and flow of node 1.

![Figure 1. Schematic diagram of the structure of the new hydraulic pulsation suppressor.](image1)

![Figure 2. Simplified model diagram of the new hydraulic pulsation suppressor.](image2)

![Figure 3. Simplified model diagram of node 1.](image3)

3 Mathematical model and attenuation characteristics analysis of the new hydraulic pulsation suppressor

It can be written by node conditions:

\[
Q_6 = \sum_{x=7}^{10} Q_x + Q_{11} \quad \text{(1)}
\]

\[
P_6 = P_7 = P_8 = P_9 = P_{10} = P_{11} \quad \text{(2)}
\]

Make

\[
Z_x = P_x/Q_x \quad \text{(3)}
\]

Where, \( x = 7, 8, 9, 10 \)

\( Z_x \) is the branch point impedance of the three-stage H-type hydraulic silencer system. Figure 5 is a schematic diagram of the structure of a three-stage H-type hydraulic silencer. According to the literature [9], the expression of \( Z_x \) is:

\[
Z_x = \frac{a_{11x}a_{22x}a_{32x} + a_{12x}a_{21x}a_{33x} - a_{11x}a_{22x}a_{33x}}{\rho csA_1(a_{21x}a_{32x} - a_{22x}a_{33x})} \quad \text{(4)}
\]
Where,  
\[ a_{11x} = \rho A_x l_x s^2 + 8\pi \rho v t_x s + K A_{1x}^2 \frac{1}{V_{1x}} \]
\[ a_{12x} = a_{21x} = -K A_{1x} A_{2x} \frac{1}{V_{1x}} \]
\[ a_{23x} = a_{32x} = -K A_{2x} A_{3x} \frac{1}{V_{2x}} \]
\[ a_{22x} = \rho A_{2x} l_x s^2 + 8\pi \rho v t_x s + K A_{2x}^2 \left( \frac{1}{V_{1x}} + \frac{1}{V_{2x}} \right) \]
\[ a_{33x} = \rho A_{3x} l_x s^2 + 8\pi \rho v t_x s + K A_{3x}^2 \left( \frac{1}{V_{2x}} + \frac{1}{V_{3x}} \right) \]

\[ \begin{bmatrix} P_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 1 \\ V_{2x} \end{bmatrix} = \begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix} \begin{bmatrix} 1 \\ V_{3x} \end{bmatrix} \]

Figure 4.  \( L \) is the length of the mass chamber; \( A \) is the cross-sectional area of the mass chamber; \( V \) is the volume of the volume chamber;

The principle diagram of the three-stage H-type hydraulic pulsation attenuator.

The transfer matrix from the inlet pipe of the hydraulic pulsation suppressor to node 1 is:

\[ \begin{bmatrix} P_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} 1 \\ V_{2x} \end{bmatrix} = \begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix} \begin{bmatrix} 1 \\ V_{3x} \end{bmatrix} \]

(5)

\[ Q_4 = \sum_{x=7}^{10} \frac{P_x}{Z_x} + Q_{11} = P_{11} \sum_{x=7}^{10} \frac{1}{Z_x} + Q_{11} \]

From (9) and (10), we get:

\[ Q_4 = C_{11} P_{11} + D_{11} \left( P_{11} \sum_{x=7}^{10} \frac{1}{Z_x} + Q_{11} \right) \]

(11)

Make \( Y = Q_{11} / P_{11} \).

Substituting into (11) formula:

\[ P_{11} = \frac{Q_4}{C_{11} + D_{11} \sum_{x=7}^{10} \frac{1}{Z_x} + D_{11} Y} \]

(12)

Incorporate the outlet pipe of the hydraulic pulsation suppressor into the dynamic impedance part. The dynamic characteristics of the pipeline and throttling load, the expression of load admittance \( Y \) can be obtained as [10]:

\[ Y = \frac{2\Delta P_f C_{22} + Q_f D_{22}}{2\Delta P_f A_{22} + Q_f B_{22}} \]

(13)

Where,  
\( \Delta P_f \) is the pressure loss of the throttle valve  
\( Q_f \) is the flow rate of the throttle valve  
\( A_{22}, B_{22}, C_{22}, D_{22} \) are the load-end pipelines to transfer matrix elements.
The anti-vibration effect of the new hydraulic pulsation suppressor is evaluated by the insertion loss $K_i$. The insertion loss not only considers the characteristics of the pulsation attenuator device and the piping system, but also considers the influence of source impedance and load impedance. The insertion loss is defined as the pressure ratio of the pipe load end before and after adding the pulsation attenuator \(^\text{[11]}\), namely

$$K_i = 20 \log \left( \frac{P_{1\prime}}{P_1} \right)$$

(14)

$P_{1\prime}$ is the use of rigid hydraulic tubing of the same length as the pulsation attenuator to replace the frequency domain pressure at the load end of the new hydraulic pulsation suppressor.

$P_{1\prime}$, $Q_{1\prime}$ and $P_{11\prime}$, $Q_{11\prime}$ are the dynamic frequency domain pressure and dynamic frequency domain flow rate at the inlet and outlet of the rigid straight hydraulic oil pipe after replacing the hydraulic pulsation attenuator with a rigid straight hydraulic oil pipe. The dynamic characteristics of the rigid hydraulic oil pipe are obtained according to the pipeline network calculation method. The equation is:

$$\begin{bmatrix} P_{1\prime} \\ Q_{1\prime} \end{bmatrix} = \begin{bmatrix} A_{33} & B_{33} \\ C_{33} & D_{33} \end{bmatrix} \begin{bmatrix} P_{11\prime} \\ Q_{11\prime} \end{bmatrix}$$

(15)

From the formula (15):

$$P_{15\prime} = \frac{Q_{1\prime}}{(C_{33} + D_{33})Y}$$

(16)

For the plunger pump with flow disturbance source, it's working condition is stable, so

$$Q_1 = Q_{1\prime}$$

(17)

Substituting (10), (16), and (17) into (14), the insertion loss of the new hydraulic pulsation suppressor can be expressed as:

$$K_i = 20 \log \left( \frac{C_{11} + D_{11} \sum_{x=1}^{10} \frac{1}{Z_x} + D_{11}Y}{C_{33} + D_{33}Y} \right)$$

(18)

4 Simulation analysis of the attenuation characteristics of the new hydraulic pulsation suppressor

Use MATLAB software to simulate the insertion loss of the original hydraulic pulsation suppressor. The basic parameters of the simulation are presented in table 1. The parameters of the throttle valve and hydraulic oil are given in table 2. The simulation frequency range is: 0 Hz–2000 Hz.

| Name               | Physical parameter | Value |
|--------------------|--------------------|-------|
| Inlet pipe         | Length $L_c$/mm    | 100   |

| Name               | Physical parameter | Value |
|--------------------|--------------------|-------|
| Quality Room 7     | Length $L_7$/mm    | 12.5  |
|                    | radius $r_7$/mm    | 60    |
| Quality Room 8     | Length $L_8$/mm    | 12.5  |
|                    | radius $r_8$/mm    | 7     |
| Quality Room 9     | Length $L_9$/mm    | 12.5  |
|                    | radius $r_9$/mm    | 6     |
| Quality Room 10    | Length $L_{10}$/mm  | 12.5  |
|                    | radius $r_{10}$/mm  | 6     |
| Restrictor pipe 1  | Length $L_{11}$/mm  | 12.5  |
|                    | radius $r_{11}$/mm  | 4     |
| Restrictor pipe 3  | Length $L_{13}$/mm  | 12.5  |
|                    | radius $r_{13}$/mm  | 12.5  |
| Restrictor pipe 5  | Length $L_{15}$/mm  | 12.5  |
|                    | radius $r_{15}$/mm  | 12.5  |
| Expansion room 1   | Length $L_{17}$/mm  | 12.5  |
|                    | radius $r_{17}$/mm  | 12.5  |
| Expansion room 2   | Length $L_{19}$/mm  | 12.5  |
|                    | radius $r_{19}$/mm  | 12.5  |
| Expansion room 3   | Length $L_{21}$/mm  | 12.5  |
|                    | radius $r_{21}$/mm  | 12.5  |
| Volume chamber 1   | Length $L_{23}$/mm  | 12.5  |
|                    | radius $r_{23}$/mm  | 12.5  |
| Volume chamber 2   | Length $L_{25}$/mm  | 12.5  |
|                    | radius $r_{25}$/mm  | 12.5  |
| Volume chamber 3   | Length $L_{27}$/mm  | 12.5  |
|                    | radius $r_{27}$/mm  | 12.5  |
| Quality Room 72    | Length $L_{29}$/mm  | 12.5  |
|                    | radius $r_{29}$/mm  | 12.5  |
| Quality Room 82    | Length $L_{31}$/mm  | 12.5  |
|                    | radius $r_{31}$/mm  | 12.5  |
| Quality Room 92    | Length $L_{33}$/mm  | 12.5  |
|                    | radius $r_{33}$/mm  | 12.5  |
| Quality Room 102   | Length $L_{35}$/mm  | 12.5  |
|                    | radius $r_{35}$/mm  | 12.5  |
| Quality Room 73    | Length $L_{37}$/mm  | 12.5  |
|                    | radius $r_{37}$/mm  | 12.5  |
| Quality Room 83    | Length $L_{39}$/mm  | 12.5  |
|                    | radius $r_{39}$/mm  | 12.5  |
| Quality Room 93    | Length $L_{41}$/mm  | 12.5  |
|                    | radius $r_{41}$/mm  | 12.5  |
| Quality Room 103   | Length $L_{43}$/mm  | 12.5  |
|                    | radius $r_{43}$/mm  | 12.5  |

Load equivalent pipeline

| Name               | Physical parameter | Value |
|--------------------|--------------------|-------|
|                    | Length $L_{eq}$/mm  | 400   |
|                    | radius $r_{eq}$/mm  | 12.5  |
Table 2. Basic parameter table of hydraulic oil and throttle valve.

| Name               | Physical parameter | Value  |
|--------------------|--------------------|--------|
| No. 32 hydraulic oil | Bulk modulus /MPa  | 1400   |
|                    | Viscosity /(Pa * s)| 0.00314|
|                    | density /(kg/m³)  | 890    |
| Throttle valve     | Differential pressure /MPa | 2.5 |
|                    | Flow /(L/min)      | 160    |

According to the above formula and the basic parameters of the simulation, the insertion loss of the hydraulic pulsation suppressor is programmed in MATLAB software as showed in Figure 5.

Figure 5 is the MATLAB simulation curve of insertion loss of the new hydraulic pulsation suppressor. It can be obtained from the figure that the attenuation effect of the hydraulic pulsation suppressor is above 50 dB in the pulsation frequency range of 20 Hz to 2000 Hz, and has a sound attenuation effect. Compared with ordinary pulsation attenuators, the attenuation effect is better and the attenuation frequency band is wider.

5 Conclusion

(1) A new type of hydraulic pulsation suppressor with compact structure is designed, and the mathematical model of the hydraulic pulsation suppressor is reasonably deduced. According to theoretical analysis, the new hydraulic pulsation suppressor achieves the effect of triple attenuation of pulsation in a wide frequency band.

(2) Through the analysis of the simulation calculation results of MATLAB software, it is found that the new hydraulic pulsation suppressor has an ideal effect of attenuating pressure pulsation in the frequency range of 20 Hz to 2000 Hz, and achieves an efficient and broad-spectrum attenuation of pressure pulsation.

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