COMPARATIVE ANALYSIS OF PERFORMANCES OF NON-METAL PRESSURIZED RESERVOIRS WITH VARIABLE VOLUME

Jing Yao[1,3], Dingyu Wang[1,3]*, Dong Liang[1,3], Jinlu Hao[1,3], Pei Wang[2,3]

[1] *State Key Laboratory of Crane Technology, Yanshan University, West of Hebei Avenue 438, 066004 Qinhuangdao, China*
[2] *Hebei Innovation Center for Equipment Lightweight Design and Manufacturing, Yanshan University, West of Hebei Avenue 438, 066004 Qinhuangdao, China*
[3] *School of Mechanical Engineering, Yanshan University, West of Hebei Avenue 438, 066004 Qinhuangdao, China*

* Corresponding author: Tel.: +86 15931165526; E-mail address: dingyu_wang@stumail.ysu.edu.cn

ABSTRACT

The lighter weight of hydraulic reservoirs can improve the power-to-weight ratio of hydraulic equipment and reduce power consumption, achieving energy conservation and emission reduction. In this study, three types of non-metal pressurized reservoirs with variable volume (VVPR) are designed and manufactured. Among them, a single-layer configuration is the basic functional prototype. Firstly, the structure of VVPR is designed to meet the differential volume compensation by its variable volume in an asymmetric hydraulic cylinder system. Then, series and parallel configurations are proposed based on the basic prototype. Finally, a test bench is built to test the step and sine response performances of the VVPR. The response time of the reservoir is not affected by the step amplitude of the hydraulic cylinder changes, with an average response time of 0.028 s. In addition, the lag time of the single-layer reservoir is the smallest in the sine test, which is 0.11 s. Through comparative analysis, the configuration of the series reservoir is more compact and can get more pressure. Parallel reservoir can get greater variable volume with the same displacement change. It provides an alternative solution for lightweight hydraulic systems in the future.

Keywords: Hydraulic Reservoir, Lightweight, Pressurized Reservoir, Variable Volume

1. INTRODUCTION

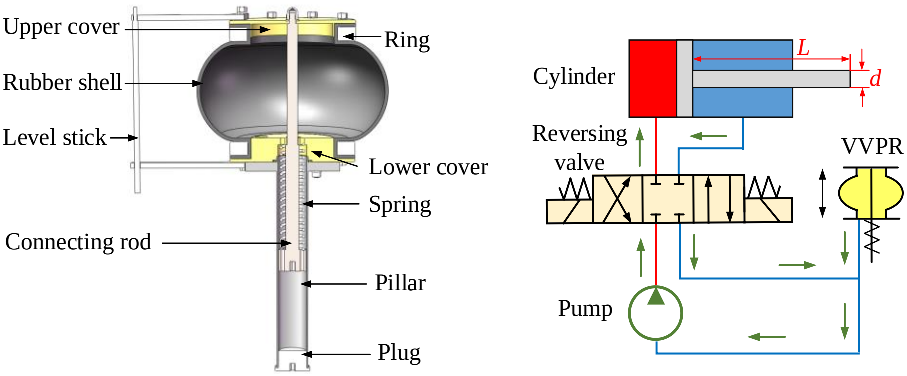
Hydraulic transmission is widely used in high-level mobile equipment such as aerospace, robotics, and engineering machinery due to its high power-to-weight ratio, fast response, and stepless speed regulation. Hydraulic systems often rely on reservoirs that are considerably larger and weigh in mobile hydraulic machinery equipment. The lightweight of hydraulic components and systems can improve the maneuverability, navigating ability, and carrying capacity of mobile equipment. The hydraulic oil reservoir is the most promising component [1], and the hydraulic oil reservoir is lightened mainly through two ways: reducing its volume and using non-metallic materials for its shell [2]. With increasing demands for reducing emissions and energy consumption, the design of hydraulic reservoirs needs to be optimized for weight and volume [3]. Traditional open reservoirs are not only bulky, but their internal oil is also prone to contamination, posing a threat to the hydraulic system. To solve the problem, ARGO-HYTOS has introduced a solution known as the "Hybrid Integrated Tank" [4]. This design leverages polyamide material to achieve exceptional mechanical strength and thermal stability, which intelligently combines the two manufacturing technologies of rotational molding and injection molding. In contrast, closed reservoirs provide smaller volume and lighter weight, and their internal oil is not susceptible to contamination. Currently, the main directions for lightweight closed hydraulic reservoirs are pressurized and variable capacity. For example, a spring-pressurized reservoir with a metal cylinder as its shell. When fluid flows into or out of the container, the spring contracts or expands in response to volume changes. At the same time, the spring generates fluid pressure by its force [5]. However, the metal construction of the reservoir results in a large volume and mass. Presently, there are emerging innovations in closed reservoirs, with a focus on novel structural designs and advanced materials for smaller volumes and lower weight [6]. To further reduce volume, the concept of variable volume reservoirs is proposed. Variable volume reservoirs are made of non-metallic materials, significantly reducing their volume and weight compared to pressurized reservoirs, providing a new method to solve the lightweight problem of reservoirs. Smart Reservoir Inc. [7] has produced a variable volume reservoir characterized by a housing crafted from a dual polymer material that exhibits remarkable chemical inertness towards hydraulic fluids. This innovation has advantages such as reduced weight, compact dimensions, and a linear output profile. It has already found application across diverse industries.

In this study, three types of non-metal pressurized reservoirs with variable volume (VVPR) are designed and manufactured. The single-layer configuration is the basic functional prototype, which is designed to meet the differential volume compensation by its variable volume in an asymmetric hydraulic cylinder system. In addition, series and parallel configurations are proposed based on the basic prototype, adapting to the compensation of more oil volume in the system.

2. CONFIGURATION DESIGN

2.1. Principle of the VVPR

The structure of VVPR is designed to meet the differential volume compensation in an asymmetric hydraulic cylinder system and increase the suction pressure of the hydraulic pump. The single-layer configuration is the basic functional prototype of the VVPR and mainly includes a rubber shell, spring, upper and lower covers, connecting rod, rings, and other components, which is shown in **Figure 1(a)**. Among them, the elastic shell made of rubber is used to store hydraulic oil. The upper cover and the connecting rod are fixedly connected and move together. The upper and lower covers are in contact and the spring is in free length during initial installation. The spring is located in the pillar and is always compressed in the working cycle of the reservoir. The compression of the spring is the same as the upward displacement of the upper cover during the working process of the VVPR. In addition, the function of absorbing and discharging oil and increasing the suction pressure of the pump is achieved through the interaction of spring force and internal pressure acting on the upper cover. The VVPR is airless, sealed, and slightly pressurized, with a small volume and lightweight.



(a) Structure of the single-layer reservoir (b) Application in the system

Figure 1: Working principle diagram of the VVPR

In the system application, the main function of the reservoir is to compensate for the volume difference of the hydraulic cylinder, which is generated by the asymmetric structure of the hydraulic cylinder, shown in **Figure 1(b)**. The valve control hydraulic system comprises a hydraulic pump, reversing valve, single-rod hydraulic cylinder, and VVPR, forming a closed loop. In the operation of the system, the hydraulic cylinder is extended and retracted by switching the reversing valve, with discharging and absorbing oil of the VVPR at the same time. In the initial application stage, air bleeding will be achieved through the exhaust valve of the upper cover. For example, when the hydraulic cylinder is extended, the oil from the outlet of the pump to the rodless chamber of the hydraulic cylinder through the reversing valve. The oil in the rod chamber enters the suction port of the pump. However, due to the different volumes of the rod and rodless chambers, the oil in the VVPR is replenished into the inlet of the pump. The hydraulic cylinder retraction process is the opposite.

In the case of not considering the system leakage and oil compression, the volume difference between all hydraulic cylinders with rod and rodless chambers in the hydraulic system is shown in Equation (1).

$$\Delta V = \sum_{i=1}^{n} \frac{\pi {d_i}^2}{4} L \tag{1}$$

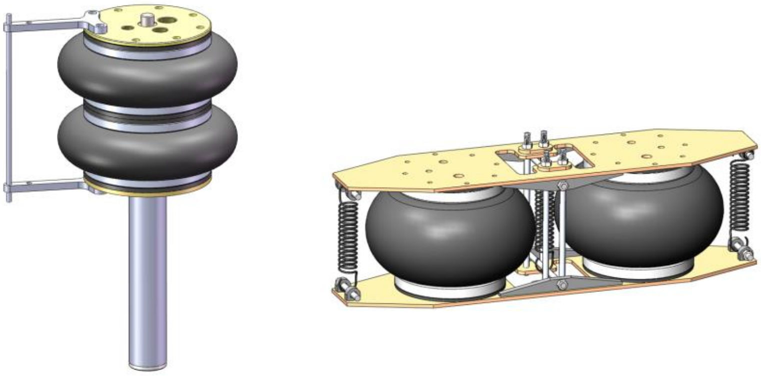
Where ΔV is the volume difference, d is the cylinder rod diameter, and L is the cylinder stroke.

Therefore, the volume of the VVPR should be designed to meet the requirements of the volume difference required by the hydraulic system.

2.2. Structural iteration

The volume and pressure of VVPR are two main performance parameters in the design stage. To adapt to the compensation of more oil volume in the system, series and parallel configurations are proposed based on the basic prototype. The series configuration is shown in **Figure 2(a)**, and it is different from a single-layer reservoir in that it comprises two single-layer rubber shells, which are connected by embedded threads in the rings. Furthermore, it can also be connected in series with multiple shells, such as three or four.

Series configuration of VVPR provides higher pressure than a single-layer reservoir, under the same length of pillar. Because the pressure of the reservoir is generated by the deformation of the spring, the higher the total shell of VVPR, the bigger the pressure provided. However, this configuration increases the vertical height of VVPR. In addition, under the same volume, the maximum outer diameter of the series configuration is smaller than that of the single-layer reservoir. The maximum outer diameter refers to the maximum radial distance of the rubber shell when the VVPR is at its maximum compression position, which reflects the compactness of the horizontal spatial layout.



(a) Series reservoir (b) Parallel reservoir

Figure 2: The configuration iteration of VVPR

The parallel configuration of VVPR is shown in **Figure 2(b)**, in which the two single-layer rubber shells are arranged in parallel, and the springs are connected between the upper and lower covers. It can also be arranged three or four rubber shells in a horizontal circumferential array. Compared with the other two configurations, it can discharge or absorb more oil under the same height change of the VVPR.

However, compared with the series configuration of VVPR, the parallel configuration reduces the vertical height but increases the size of the horizontal space occupied by the VVPR in the working state. The spring used in the parallel configuration is the tension spring rather than a compression spring. Moreover, to obtain the same pressure, more springs need to be connected in parallel to improve spring stiffness, due to the increase in the pressed area of the upper cover.

Advantages of the VVPR:

- Adapt to the change of oil volume in the system.
- Lightweight, small volume and low cost.
- Compared with the bladder accumulator, temperature variation does not affect the pressure variation by use of a mechanical spring. In addition, no gas is required.

When the VVPR is used in a hydraulic system, the configuration design can be reasonably selected according to the spatial layout of the system.

3. MODEL DEVELOPMENT

Take the single-layer configuration of VVPR as an example. The variable volume function of the reservoir is realized by the compression deformation of the rubber shell of VVPR, shown in **Figure 3**. Besides, the spring force generated by spring deformation is transmitted to the upper cover through the connecting rod to realize oil pressurization of the VVPR. The relationship between volume, pressure, and structural parameters can be obtained through geometric and force analysis.

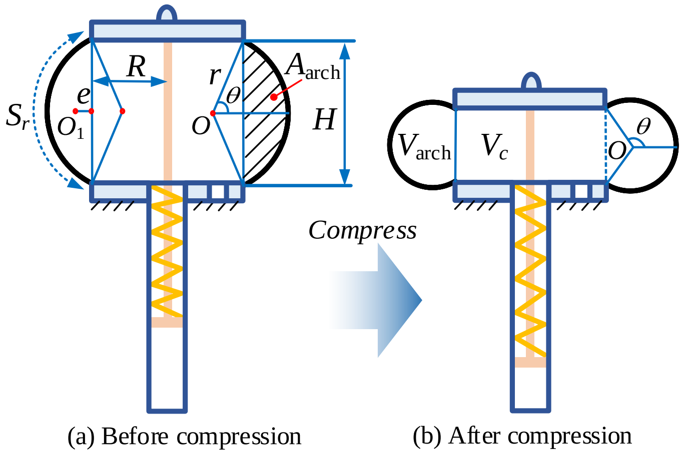


Figure 3: Compression deformation of the rubber shell of VVPR

3.1. Geometrical analysis

In this section, the relationship between the volume of the reservoir and the height of the rubber shell will be studied. According to the structure of the reservoir, the rubber shell is a body of revolution. The longitudinal cross-section of the rubber shell and structural parameters are illustrated in **Figure 3(a)**.

The following two hypotheses are proposed to simplify the analytical process of the geometric model:

- The length of the curved longitudinal cross-section is constant while the height of the reservoir changes.

- The curve is always arc-shaped in the process of reservoir work.

The height of the reservoir is calculated as shown in Equation (2).

$$H = 2r\sin\theta \tag{2}$$

where r is the radius of the arc, θ is the half-central angle of the arc.

The relationship between arc length and half-central angle is as follows.

$$S_r = 2r\theta \tag{3}$$

Combining Equation (2) and Equation (3), the expression of reservoir height can be calculated as:

$$H = \frac{S_r\sin\theta}{\theta} \tag{4}$$

According to **Figure 3(b)**, the structural volume of the single-layer reservoir is given by:

$$V_1 = V_c + V_{\text{arch}} \tag{5}$$

where V_c is the volume of the cylinder between the upper cover and lower cover, V_{arch} is toroidal volume which is formed by an arch rotating around the central axis. V_c is calculated as:

$$V_c = \pi R^2 H \tag{6}$$

where R is the radius of the upper and lower cover. V_{arch} is calculated as:

$$V_{\text{arch}} = 2\pi(R+e)A_{\text{arch}} \tag{7}$$

where A_{arch} is the arch area and e is the distance from the centroid O_1 of the arch to the arc chord. According to the geometrical relationship, A_{arch} and e can be derived as follows [8].

$$A_{\text{arch}} = \frac{r^2(2\theta - \sin 2\theta)}{2} \tag{8}$$

And

$$e = r\left[\frac{4\sin^3\theta}{3(2\theta - \sin 2\theta)} - \cos\theta\right] \tag{9}$$

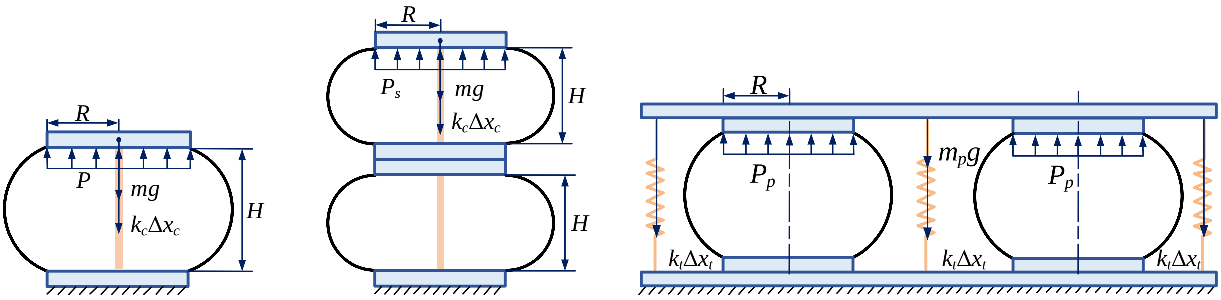
Therefore, the structural volume V_1 of the single-layer reservoir can be written as:

$$V_1 = \pi R^2 H + \frac{\pi {S_r}^2}{4\theta^2}(2\theta - \sin 2\theta)\left\{R + \frac{S_r}{2\theta}\left[\frac{4\sin^3\theta}{3(2\theta - \sin 2\theta)} - \cos\theta\right]\right\} \tag{10}$$

The volume expressions of the combined reservoirs can also be derived by using Equation (10). Assuming that the shape of the two rubber shells has the same change when the height of VVPR changes. The volume of both series and parallel reservoirs is two times that of the single-layer reservoir. During the volume changes, the maximum height of the parallel reservoir is the same as the height of the single-layer reservoir, while the maximum height of the series reservoir is twice the height of the single-layer reservoir.

3.2. Force analysis

During the operation of absorbing oil of the VVPR, the volume change of oil drives the upper cover of the reservoir upward, which causes the spring to compress, and the spring force acts on the oil through the upper cover to achieve the purpose of pressurization. Ignore the slight influence of the elastic rubber shell on the upper cover. In the state of force balance, the force analysis of the upper cover of the single-layer reservoir is shown in **Figure 4(a)**.



(a) single-layer reservoir (b) series reservoir (c) parallel reservoir

Figure 4: Force analysis of the VVPR

The upper cover stops moving when the maximum volume of oil is reached, at which point the maximum pressure of oil can be obtained from the reservoir.

$$P = \frac{mg + k_c \Delta x_c}{\pi R^2} \tag{11}$$

where m is the mass of the single upper cover, P is the pressure of the single-layer reservoir, k_c is the stiffness of the compression spring, Δx_c is the compression of the spring, $\Delta x_c=H$.

It is clear to see that the maximum output pressure of the reservoir is determined by the height of the reservoir and the area of the upper cover.

Similarly, the maximum output pressure of the corresponding configuration can be obtained according to the force analysis of the series reservoir and the parallel reservoir. The force analysis of the series reservoir is shown in **Figure 4(b)**.

According to the force analysis, when the displacement of the upper cover of the series reservoir is maximum, where $\Delta x_c=2H$. The pressure of a series reservoir can be obtained.

$$P_s = \frac{mg + 2k_c H}{\pi R^2} \tag{12}$$

The force analysis of the parallel reservoir is shown in **Figure 4(c)**. According to the force analysis, the maximum output pressure of the parallel reservoir is as follows.

$$P_p = \frac{m_p g + n k_t \Delta x_t}{2\pi R^2} \tag{13}$$

where P_p is the output pressure of the parallel reservoir, k_t is the stiffness of the tension spring, n is the number of the tension springs, m_p is the mass of the upper cover of the parallel reservoir, Δx_t is the stretching length of the tension spring, $\Delta x_t=H-l_0$, l_0 is the free length of tension spring.

By comparison, among the three configurations of VVPR, the series reservoir can provide the maximum output pressure.

3.3. Comparison of configurations

By comparing and analyzing the characteristics of the three configurations of VVPR, the results are as follows:

- Single-layer configuration of VVPR

As a basic configuration, the VVPR is convenient to process and install, but when the demand of volume difference is large, it needs a plurality of integral single-layer reservoirs to be used in parallel and connected to the oil suction port through oil pipes.

- Series configuration of VVPR
  This configuration can have higher pressure and good space compactness, but it increases the difficulty of installation adjustment and vertical height of the VVPR.
- Parallel configuration of VVPR
  The variable volume is the largest under the same displacement. In addition, it is easy to maintain and replace components, because the spring is installed externally. However, it occupies more horizontal space and requires multiple springs.

4. TEST AND ANALYSIS

4.1. Prototype and test principle

Based on the mathematical model, three types of reservoir prototypes are designed and manufactured, including single-layer, series, and parallel configurations, as shown in **Figure 5**. The primary parameters of prototypes are shown in **Table 1**.

Figure 5: Prototype of the VVPR: (a) Single-layer reservoir (b) Series reservoir (c) Parallel reservoir

Table 1: Parameters of three configurations

Parameter	Single-layer reservoir	Series reservoir	Parallel reservoir
Structural volume [l]	1	2	2
Variable volume [l]	0.8	1.6	0.8
Pressure [bar]	0.2-0.51	0.15-0.65	0.15-0.62
Total weight of VVPR [kg]	6.3	7.2	13.9
Radius of upper cover [mm]	68	68	68

A test bench is established for the static and dynamic performance of three reservoirs. The test principle is shown in **Figure 6**. The parameters of the hydraulic system are shown in **Table 2**. By changing the state of the cut-off valves, static testing of the VVPR can be carried out. During dynamic testing, the right hydraulic cylinder is connected to the VVPR, and step and sine response tests are conducted on the VVPR through a directional valve controlled hydraulic cylinder.

Table 2: Parameters of hydraulic system

Parameter	Value
System pressure [MPa]	10
System flow [l/min]	20
Cylinder diameter [mm]	100
Cylinder rod diameter [mm]	70
Hydraulic cylinder stroke [mm]	250

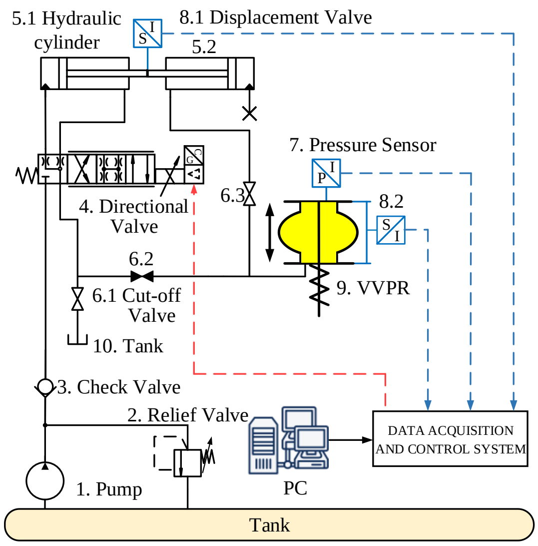


Figure 6: The VVPR test principle

4.2. Static performance analysis

The static performance test is to determine the relationship between pressure, displacement and variable volume during the oil charge and discharge of the three reservoirs, and the results are shown in **Figure 7**.

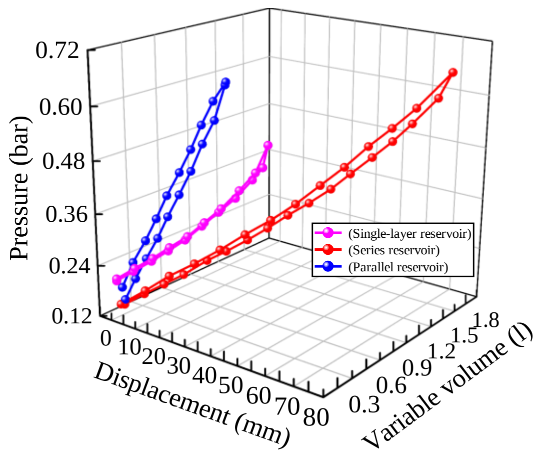
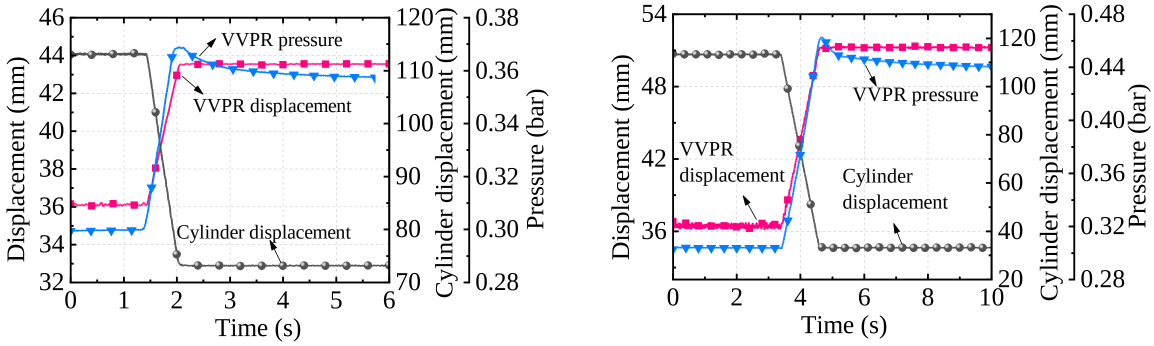


Figure 7: Static performance test results of the VVPR

The pressure and variable volume of the reservoir increase with the increase of displacement. Taking the oil charge process of the series reservoir as an example, when the displacement is 2.13-71.73 mm, the oil charge volume increases from 0.058 l to 1.624 l, and the pressure increases from 0.157 bar to 0.653 bar. In addition, it can be seen that the static test curves of the VVPR do not coincide during the oil charge and discharge, showing obvious hysteresis, in which the hysteresis of the single-layer reservoir is the smallest. Through comparative analysis, the series reservoir can get more pressure. Parallel reservoir can get greater variable volume with the same displacement change.

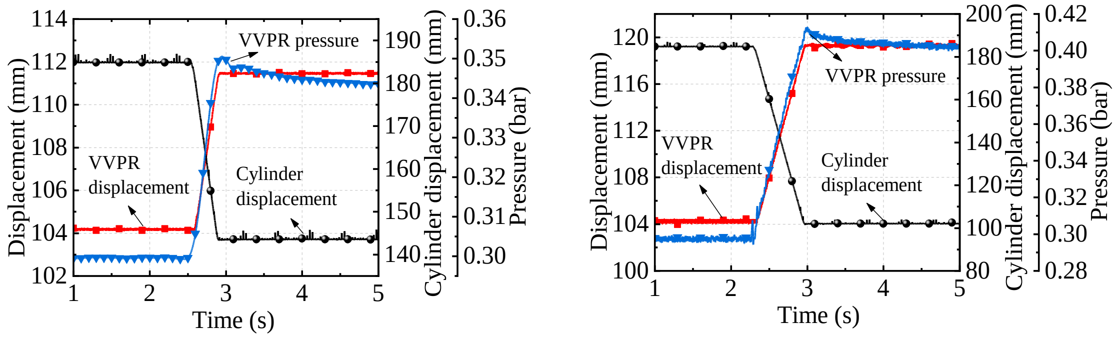
4.3. Dynamic performance analysis

To compare the step response performance of different reservoir configurations, the initial pressure of the reservoir is set at 0.3 bar, and the stroke change of the hydraulic cylinder is 40 mm/80 mm. The step response test curves are shown in **Figure 8-10**. The hydraulic cylinder retracts at 1.428 s, and after a response time of 0.028 s, the pressure of the VVPR increases. After a rise time of 0.72 s, the pressure increases by 0.057 bar and reaches stability, as shown in **Figure 8(a)**. In the experiment, due to the large instantaneous flow rate caused by the hydraulic cylinder, the pressure of the VVPR is overshooted, and the pressure overshoot of the parallel reservoir is the smallest.



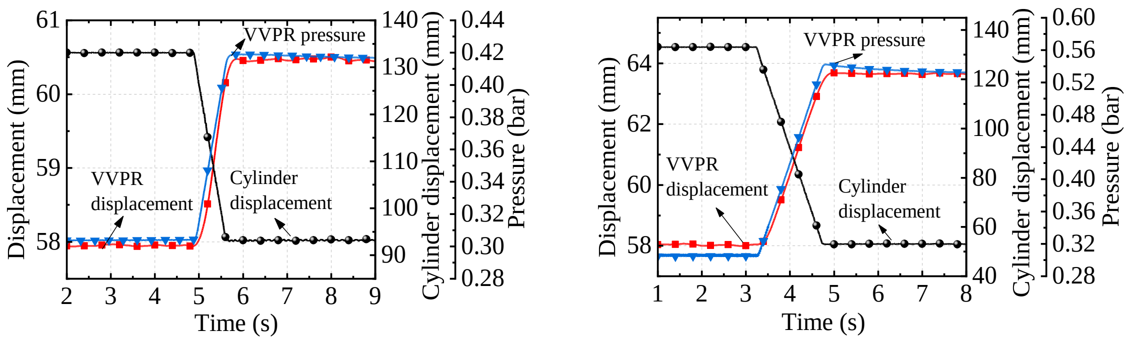
(a) 0.3 bar step amplitude of 40 mm (b) 0.3 bar step amplitude of 80 mm

Figure 8: Step response test curve of the single-layer reservoir



(a) 0.3 bar step amplitude of 40 mm (b) 0.3 bar step amplitude of 80 mm

Figure 9: Step response test curve of the series reservoir



(a) 0.3 bar step amplitude of 40 mm (b) 0.3 bar step amplitude of 80 mm

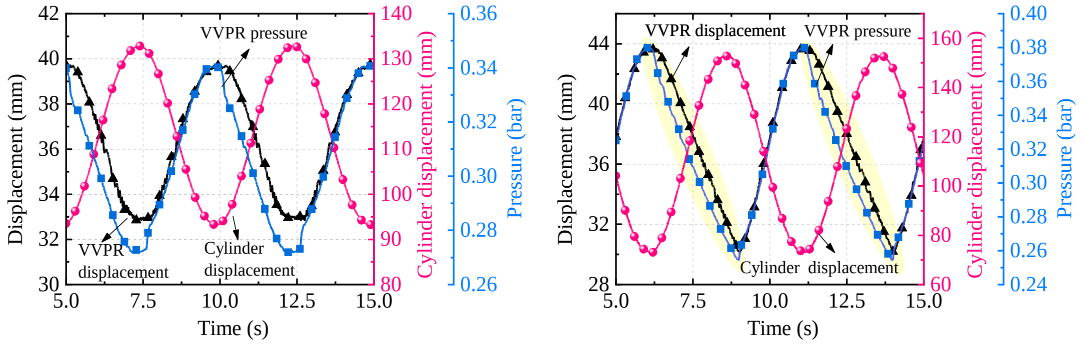
Figure 10: Step response test curve of the parallel reservoir

Taking reservoir pressure as an example, the rise time and pressure variation amplitude are shown in **Table 3**. As the step amplitude of the hydraulic cylinder increases, the rise time and change amplitude of the reservoir pressure curve gradually increase. Among them, the rise time of the parallel reservoir is the longest. The response time of the reservoir is not affected by the step amplitude of the hydraulic cylinder changes, with an average response time of 0.028 s.

Table 3: Step response parameters of the VVPR

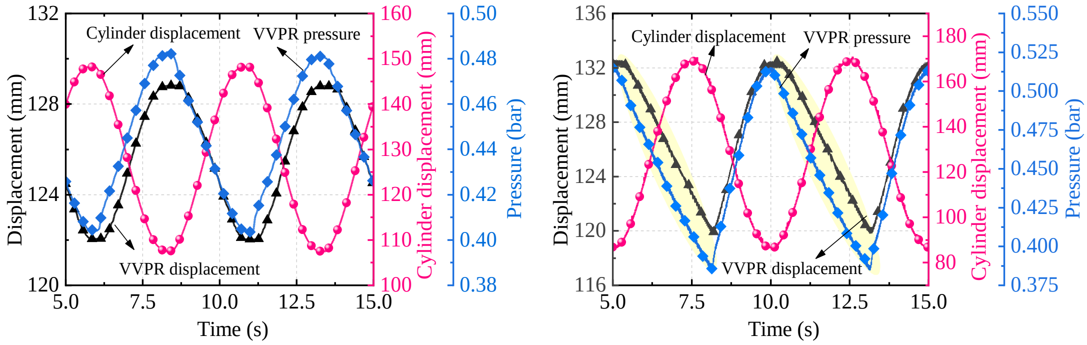
Parameter	Single-layer reservoir		Series reservoir		Parallel reservoir	
Step amplitude [mm]	40	80	40	80	40	80
Response time [s]	0.028	0.026	0.03	0.035	0.02	0.03
Rise time [s]	0.72	1.26	0.44	0.71	0.85	1.54
Pressure variation amplitude [bar]	0.057	0.141	0.044	0.104	0.117	0.229

The sine response test curves with 0.2 Hz ±20 mm/40 mm are shown in **Figure 11-13**, which are the results of single-layer reservoir, series reservoir and parallel reservoir respectively. It is clear that the corresponding pressure and displacement of the VVPR also change with the response of the extension and retraction of the hydraulic cylinder. For example, when the hydraulic cylinder is extended, the VVPR discharges oil, and the displacement and pressure of the VVPR gradually decrease.



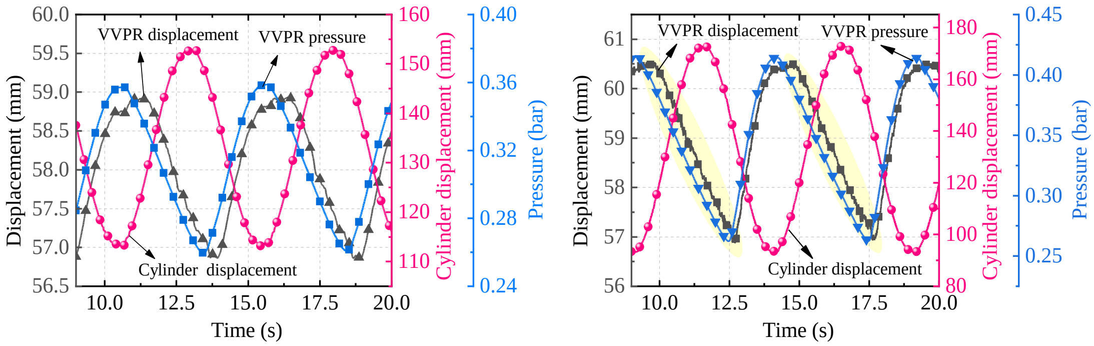
(a) Sine test with 0.2 Hz ±20 mm (b) Sine test with 0.2 Hz ±40 mm

Figure 11: Sine response test curve of the single-layer reservoir



(a) Sine test with 0.2 Hz ±20 mm (b) Sine test with 0.2 Hz ±40 mm

Figure 12: Sine response test curve of the series reservoir



(a) Sine test with 0.2 Hz ±20 mm (b) Sine test with 0.2 Hz ±40 mm

Figure 13: Sine response test curve of the parallel reservoir

According to the test results, the sine response parameters of the VVPR are shown in **Table 4**, and the lag time is the time for the reservoir displacement response to lag behind the hydraulic cylinder displacement response. For example, when the working amplitude of the hydraulic cylinder is 20 mm, the single-layer reservoir lags behind the hydraulic cylinder by 0.11 s, with a phase difference of 0.04π. With the increase of the sinusoidal amplitude of the hydraulic cylinder, the lag phase difference of the reservoir also increases. In addition, with the increase of the amplitude, the displacement and pressure of the reservoir are lagging, and there is a “sharp point” (marked by the yellow area).

Compared with the three configurations, the lag time of the single-layer reservoir is the smallest under the same amplitude.

Table 4: Sine response parameters of the VVPR

Parameter	Single-layer reservoir		Series reservoir		Parallel reservoir	
amplitude [mm]	20	40	20	40	20	40
Lag time (s)	0.11	0.43	0.12	0.68	0.79	1.06
Lag phase difference	0.04π	0.17π	0.05π	0.27π	0.32π	0.42π

5. CONCLUSION AND OUTLOOK

In this study, three different configurations of VVPR are designed and tested, and their performance parameter, structural differences and applicable space occasions are compared. The VVPR can compensate for the volume difference in the hydraulic system and provide pressure for the pump oil supply.

Based on the geometric and force analysis, the relationship among volume, pressure and structural parameters can be obtained. Three prototypes of the reservoir are manufactured. Through comparative analysis, the configuration of the series reservoir is more compact and can get more pressure. Parallel reservoir can get greater variable volume with the same displacement change. In addition, a test bench is built to test the step and sine response performances of the VVPR. The experimental results indicate that in the sine test, the reservoir follows the action of the actuator, but there is a slight delay compared to the movement of the hydraulic cylinder due to the influence of oil flow. The response time of the reservoir is not affected by the step amplitude of the hydraulic cylinder changes, with an average response time of 0.028 s. Compared with the three configurations, the lag time of the single-layer reservoir is the smallest, which is 0.11 s. However, there are a large number of charging and discharging cycles in the application of the VVPR, and the fatigue characteristics deserve further study.

ACKNOWLEDGEMENTS

This work was funded by the National Key Research and Development Program of China (No. 2018YFB2000703).

NOMENCLATURE

d	The cylinder rod diameter	mm
L	Cylinder stroke	mm
ΔV	Volume difference	l
r	The radius of the arc	mm
θ	The half-central angle of the arc	rad
H	The height of the reservoir	mm
S_r	Arc length	mm
R	The radius of the upper and lower cover	mm
V_1	The volume of the single-layer reservoir	l
V_c	The volume of the cylinder between the upper cover and the lower cover	l
V_{arch}	The volume of the body of revolution which is formed by the arch rotating around the central axis	l
A_{arch}	The arch area	mm^2

e	The distance from the centroid O_1 of the arch to the arc chord	mm
P	The pressure of the single-layer reservoir	bar
P_s	The pressure of the series reservoir	bar
P_p	The pressure of the parallel reservoir	bar
m	The mass of the single upper cover	kg
m_p	The mass of the upper cover of the parallel reservoir	kg
k_c	The stiffness of the compression spring	N/mm
Δx_c	The compression of the spring	mm
k_t	The stiffness of the tension spring	N/mm
n	The number of the tension springs	-
l_0	The free length of the tension spring	mm
Δx_t	The stretching length of the tension spring	mm

REFERENCES

[1] Kong X D, Zhu Q X, Yao J, Shang Y X, Zhu Y (2021). Basic theory and key technology of “new method for lightweight design and manufacturing of hydraulic components and systems”. Journal of Mechanical Engineering, 57(24), 4-12.

[2] Kong X D, Zhu Q X, Yao J, Shang Y X, Zhu Y (2020) Reviews of lightweight development of hydraulic components and systems for high-level mobile equipment. Journal of Yanshan University, 44(03), 203-217.

[3] Qi G F, Zhang J J, Sun J G (2011) Miniaturization trend of the hydraulic fuel tank and the new trend of development. Machine Tool & Hydraulics, 39(24), 66-68, 104

[4] Wartlick K, Baumann M, Veres A, Weidemann R (2020) CFD-aided optimization of customer-specific tank systems using an innovative labyrinth deaerator. 12th International Fluid Power Conference, Dresden, 2020.

[5] Ouyang X P, Fan B Q, Yang H Y, Ding S (2016) A novel multi-objective optimization method for the pressurized reservoir in hydraulic robotics. Journal of Zhejiang University-SCIENCE A, 17(6), 454-467.

[6] Wang P, Yao J, Feng B D, Li M D, Wang D Y (2022) Modelling and dynamic characteristics for a non-metal pressurized reservoir with variable volume. Chinese Journal of Mechanical Engineering, 35(1), 1-15.

[7] Seguin C (2003) Variable volume reservoir. US20030136123A1.

[8] Chen J J, Yin Z H, Rakheja S, He J H, Guo K H (2018) Theoretical modelling and experimental analysis of the vertical stiffness of a convoluted air spring including the effect of the stiffness of the bellows. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 232(4), 547-561.