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Research on the Vibration Reduction Performance of Swing Cylinder Type Hydro-pneumatic Suspension for Tracked Vehicles

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Abstract: *Suspension system has an important influence on ride comfort and handling stability of vehicles. This paper cites the swing cylinder hydro-pneumatic suspension of tracked vehicles as the study object, and experimental study on the vibration damping performance of the swing cylinder hydro-pneumatic suspension is carried out. Firstly, the mathematical models of stiffness and damping of the swing cylinder hydraulic suspension were established, and the stiffness and damping characteristics of the suspension system were analyzed with road simulation tests. Then, the vehicle body vibration tests under different speed and initial pressure of swing cylinder were carried out. Next, the evaluation index and its quantification algorithm reflecting the performance of the tracked vehicle suspension system were analyzed and proposed, and the weight distribution was achieved by multi-index information fusion. Finally, taking the initial pressure of swing cylinder as the test variable, optimization design and analysis with the initial pressure of the oscillating cylinder as the test variable are carried out. The test results show that the reasonable distribution of the initial pressure of each swing cylinder is of great practical significance to improve the comprehensive vibration reduction performance of the suspension system.*

Keywords: *Swing cylinder type hydro-pneumatic suspension, Road simulation test, Initial pressure, Performance index, Orthogonal test*

1. Introduction

Hydro-pneumatic suspension systems use nitrogen as the elastic medium and hydraulic fluid for pressure transmission. The hydraulic fluid flows through the damping valve system to produce damping and reduce vibrations. This integrated system combines the functions of traditional suspension components into a compact and efficient design, offering high energy density and ease of installation. Widely used in tracked vehicles[1,2], it has been the subject of extensive research focused on improving vibration damping performance. Key areas of study include numerical simulations of vibration characteristics[3,4], optimization designs[5,6], control technologies[7,8,9], and single-axis suspension vibration tests[10,11].

Currently, most studies on hydro-pneumatic suspension use single-wheel test rigs due to experimental limitations. However, tracked vehicles, being multi-axle vehicles, are influenced by factors such as body structure and mass distribution, leading to a non-uniform arrangement of load-bearing wheels. This non-uniform distribution of dynamic parameters across various suspension branches affects ride comfort and operational stability. Therefore, merely applying equal parameter distribution across all branches is unlikely to achieve optimal vibration damping. In the swing cylinder-type hydro-pneumatic suspension system examined in this study, aside from the initial pressure of the swing cylinder, other suspension parameters (such as the damping orifice area and the lengths of the upper and lower arms of the balance lever) are difficult to adjust. The initial pressure of the swing cylinder affects the stiffness and damping characteristics of the suspension[12], thereby influencing the vibration damping performance of the tracked vehicle suspension. Additionally, conducting road tests for tracked vehicles on actual roads involves high costs and significant workloads. This paper investigates the effect of swing cylinder pressure on the vibration damping performance of hydro-pneumatic suspensions for tracked vehicles using a road simulation test bench. It examines how different pressures impact the stiffness and damping

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characteristics of the suspension and their influence on vehicle body vibrations. An orthogonal experimental design is used to develop a test plan for swing cylinder pressure distribution. Orthogonal experiments and grey relational analysis are then performed to assess the impact of swing cylinder pressure on tracked vehicle vibrations. This research provides a theoretical basis for semi-active control and suspension system design, offering practical insights to enhance the vibration damping performance of hydro-pneumatic suspensions in tracked vehicles.

2. Experimental Conditions

2.1 Road Simulation Test Bench

The road simulation test bench (Fig 1) is an experimental system designed to replicate the loads and vibrations a vehicle experiences during driving. It creates a controlled and repeatable environment that closely mimics real-world conditions, making it valuable for vehicle testing. Before conducting experiments, sensors including accelerometers, inclinometers, displacement sensors, and pressure sensors are installed on the test vehicle to gather the necessary data.

Figure 1: Road simulates test-bed

2.2 Basic Structure of the Oscillating Cylinder Type Hydro-Pneumatic Suspension

The hydro-pneumatic suspension for tracked vehicles includes oscillating cylinder, fixed cylinder, and internal hinge types. This study focuses on the oscillating cylinder type, a multi-axle suspension system with six branch suspensions. As shown in Fig 2, the key components are the oscillating cylinder, balancing lever, and accumulator. The oscillating cylinder is connected to the vehicle body via a pin, with one oil port linked to an accumulator filled with high-pressure nitrogen. The piston rod connects to the upper arm of the balancing lever, while the road wheel is mounted on the lower arm.

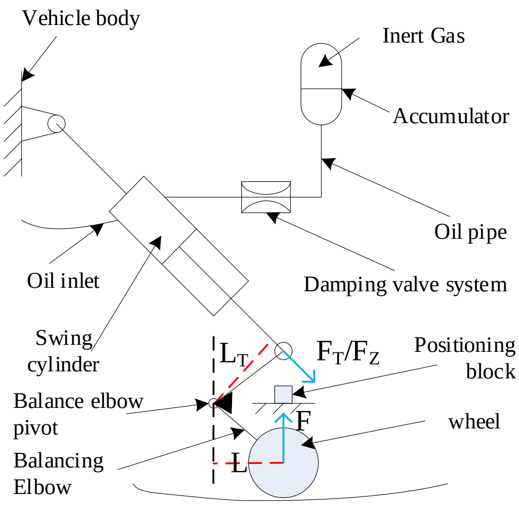

Figure 2: Oil-gas suspension structure of swing cylinder

Each branch of the hydro-pneumatic suspension pivots around the balancing lever. When the road wheel moves closer to the vehicle body, the oscillating cylinder compresses, opening the valve, which allows oil to flow into the accumulator. This compresses the nitrogen gas, providing an elastic buffer. When the wheel moves away, the gas chamber expands, the valve closes, and oil returns to the oscillating cylinder. The balancing lever rebounds, extending the piston rod and increasing the wheel's distance. This process generates a damping force that reduces vibration.

3. Analysis of the Characteristics of Oscillating Cylinder Hydro-Pneumatic Suspension

3.1 Mathematical Model of Stiffness and Damping for Oscillating Cylinder Hydro-Pneumatic Suspension

The stiffness and damping of the swing cylinder-type hydro-pneumatic suspension exhibit nonlinear characteristics. After manufacturing, stiffness is primarily determined by the pressure in the rodless chamber of the swing cylinder, with damping characteristics also varying under different pressures[12]. To analyze the impact of swing cylinder pressure on suspension stiffness and damping, a mathematical model is established. The model assumes[13]: (1) Sufficient lubrication between the piston and cylinder wall, neglecting friction damping; (2) The rod chamber is connected to the oil tank, with negligible oil pressure; (3) Damping in the oil pipe is negligible compared to the damping valve system; (4) Oil compressibility is negligible compared to gas in the accumulator; (5) No oil leakage occurs, and temperature effects on the suspension are ignored. The state equation for the gas in the accumulator is then formulated:

$$pV^{r}(x) = p_0 V_0^{r} \tag{1}$$

In the equation, p_0 represents the gas pressure in the accumulator in its initial state, V_0 is the volume of the gas in the accumulator in its initial state, p_0 is the dynamic gas pressure in the accumulator, and $V(x)$ is the dynamic volume of the gas in the accumulator, which is a function of the travel x of the load-bearing wheel. The specific calculation of $V(x)$ will not be elaborated upon in this paper. r is the polytropic index of the gas.

Conducting a force analysis on the piston of the swing cylinder, we note that due to the very slow loading speed during the static characteristic test, the hydraulic oil pressure at both ends of the oil-gas spring damping valve system is nearly equal, thus the damping effect can be neglected. The elastic force F_T acting on the piston of the swing cylinder can be expressed as follows:

$$F_T = \left(p - p_a\right) A \tag{2}$$

In the equation, p_a is the standard atmospheric pressure; A is the cross-sectional area of the piston in the rodless chamber of the swing cylinder. The balance of elastic forces acting on the balance arm, when the load wheel rotates around the balance arm, can be expressed as follows:

$$F_T L_T = FL \Leftrightarrow F = F_T i \tag{3}$$

In the equation, L_T is the moment arm of the elastic force of the hydro-pneumatic spring acting on the balance arm; L is the moment arm of the vertical force exerted by the ground on the load wheel acting on the balance arm; F_T is the elastic force of the hydro-pneumatic spring; F is the elastic force of the hydro-pneumatic spring converted to the load wheel axle; i is the lever ratio. By combining equations (1), (2), and (3) and differentiating F, the stiffness k of the hydro-pneumatic suspension can be obtained as follows:

$$k = \frac{dF}{dx} \tag{4}$$

According to the orifice throttling theory, the throttling flow equation for the flow through the damping orifice and the check valve is:

$$Q = \left\{ C_d A_d + C_v A_v \left[0.5 + 0.5 sign\left(dh(x)\right) \right] \right\} \sqrt{\frac{2\Delta p}{\rho}} \tag{5}$$

In the formula, Q represents the flow rate through the small orifice; C_d and are C_v the flow

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coefficients; A_d is the cross-sectional area of the damping orifice; A_v is the cross-sectional area of the check valve; ρ is the fluid density; $h(x)$ is the piston stroke as a function of the load wheel stroke x, and the detailed calculation process is not elaborated here; $dh(x)$ is the piston movement speed in the swing cylinder's rodless chamber. During the operation of the hydro-pneumatic suspension, the relationship between the oil flow through the check valve and the damping orifice and the piston speed is given by:

$$Q = Adh(x) \tag{6}$$

The pressure drop loss Δp caused by the accumulator outlet check valve and the damping orifice is:

$$\Delta p = \frac{\rho A^2 \left[dh(x)\right]^2 sign\left(dh(x)\right)}{2\left\{C_v A_v + 0.5 C_d A_d \left[1 + sign\left(dh(x)\right)\right]\right\}^2} \tag{7}$$

In the formula, $sign(dh)$ represents the sign function and the damping force of the hydro-pneumatic spring is $F_Z = \Delta pA$. Similarly, the damping force F_f of hydro-pneumatic suspension can be obtained as:

$$F_f = F_Z i \tag{8}$$

3.2 The impact of swing cylinder pressure on suspension stiffness and damping

The established mathematical models for stiffness and damping reveal key relationships: swing cylinder pressure vs. load wheel stroke, suspension stiffness vs. swing cylinder pressure, and damping force vs. load wheel speed. Theoretical curves are shown in Fig 3 to 4. Experiments analyzed the impact of swing cylinder pressure on suspension stiffness and damping. With the vehicle fixed, hydraulic oil maintained initial pressure in the swing cylinder. During stiffness testing, vertical displacement of the load wheel increased cylinder pressure. Results show that suspension stiffness increases nonlinearly with higher swing cylinder pressure, as illustrated in Fig 3 and 4.

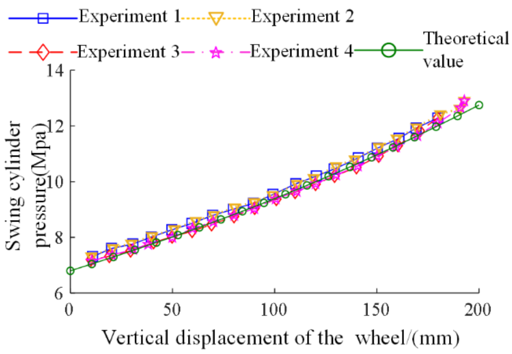

Figure 3: Relationship between initial pressure of swing cylinder and travel of bearing wheel

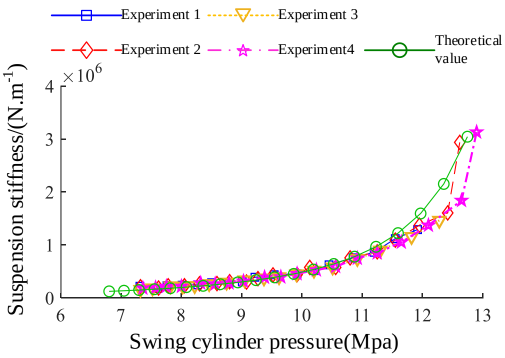

Figure 4: Relationship between suspension stiffness and swing cylinder pressure

4. The impact of swing cylinder pressure on vehicle body vibration

The analysis on the suspension's stiffness and damping characteristics revealed that swing cylinder pressure significantly influences these properties. To further investigate, an experiment was conducted to study the impact of swing cylinder pressure on vehicle body vibration. The test utilized a road simulation bench replicating the Gobi road's surface at vehicle speeds of 5、15 and 25 km/h. The initial pressures in the swing cylinders were set to 6 MPa, 8 MPa, 10 MPa, and 12 MPa. Acceleration sensors were placed above the first load wheel, at the vehicle body's center of mass, and above the sixth load wheel. Vibration was measured using the RMS value of the acceleration (Tab 1). Results showed that as the swing cylinder pressure increased, vibration acceleration generally increased at all three points. Notably, at 10 MPa, the vibration at measurement points 1 was lower than at 8 MPa, indicating that the relationship between vibration and swing cylinder pressure is not straightforward. To further explore this, the paper proposes conducting distribution experiments with varying initial pressures in each suspension branch.

Table 1: Test the relationship between point acceleration and vehicle

Vehicle speed($km.h^{-1}$)		5				15				25			
Swing cylinder pressure (Mpa)		6	8	10	12	6	8	10	12	6	8	10	12
Measurement point 1	RMS ($m.s^{-2}$)	1.66	1.74	1.66	1.76	18.33	19.33	18.72	19.06	46.40	50.80	48.68	53.27
Measurement point 2		0.78	0.86	1.02	1.43	2.29	2.89	3.31	3.93	5.62	6.22	7.33	8.38
Measurement point 3		1.69	1.73	1.70	1.95	15.36	16.06	16.36	17.30	38.01	40.11	41.53	43.18

5. Study on Swing Cylinder Pressure Distribution Experiment

5.1 Design of Vibration Damping Performance Evaluation Metrics

Before conducting the swing cylinder initial pressure distribution experiment, it is essential to design evaluation metrics for the suspension system's damping performance. Typically, these metrics focus on analyzing the impact of the suspension system on ride comfort and handling stability, with primary evaluation indicators being the RMS value of the vehicle body acceleration and the RMS value of the dynamic wheel load. However, for tracked vehicles, in addition to ride smoothness and mobility, the stability of the fire control system platform must also be considered, leading to different performance evaluation metrics. This paper proposes five performance evaluation metrics for the suspension system, which are:(1)The vertical acceleration of the vehicle body above the first load wheel. (2)The dynamic displacement of the first load wheel relative to the vehicle body. (3)The vertical motion velocity of the first load wheel relative to the vehicle body. (4)The pitch angle acceleration of the vehicle body. (5)The dynamic load coefficient of the first load wheel relative to the ground. To better evaluate and analyze the suspension system's performance, these proposed metrics need to be quantitatively described. The five metrics are represented as e_1, e_2, e_3, e_4, e_5 respectively.

5.2 Design of the Swing Cylinder Pressure Distribution Test Plan

Generally, the vertical vibration period and the pitch vibration period of tracked vehicles are respectively: $T_Z = 0.5 \sim 1s$, $T_\varphi = 0.8 \sim 1.55s$. The vertical free vibration frequency ω_z and the pitch free vibration frequency ω_y of the vehicle body are shown in Equations (9).

$$\omega_z = \sqrt{\frac{2\sum_{i=1}^{n} K_i}{M_0}}, \quad \omega_y = \sqrt{\frac{2\sum_{i=1}^{n} K_i l_i^2}{J_y}} \tag{9}$$

where K_i is the stiffness coefficient of each swing cylinder, l_i is the horizontal distance from each load wheel to the vehicle body's center of mass, M_0 is the vehicle body mass, and J_y is the moment of inertia of the vehicle body about the transverse axis through the vehicle body's center of mass. After selecting the vibration period T, the natural frequency of vibration can be determined, and thus the stiffness coefficient k of the suspension can be preliminarily determined. Finally, according to the relationship between the swing cylinder pressure and suspension stiffness shown in Fig 4, the pressure range for each swing cylinder can be determined. Calculations indicate that an initial pressure range of 5.3 MPa to 12.4 MPa is suitable for the swing cylinders of tracked vehicles.

Since the initial pressure of the swing cylinder influences suspension stiffness and damping, and is easier to adjust compared to other parameters, this paper uses it as the experimental indicator. To balance vehicle body and minimize factors, an orthogonal test table $L_{27}(3^{13})$ is chosen. The experimental factors are the initial pressures of the six branch suspensions, each with three levels: 6 MPa, 9 MPa, and 12 MPa. This approach facilitates the design of the experimental plan.

5.3 Orthogonal Test Analysis

According to the orthogonal test table, 27 suspension system vibration damping performance evaluation tests will be conducted. The input conditions for each test are the same, simulating a Gobi road surface at a vehicle speed of 25 km/h. Using the five previously mentioned vibration damping performance evaluation metrics, the metric values corresponding to each test number are calculated. For ease of subsequent processing and normalization of each metric. It is evident that it is difficult to discern the impact of swing cylinder pressure on the suspension vibration damping performance based on a single metric. Therefore, the five-performance metrics were integrated. The key to integrating the metrics is determining the weight coefficients for each performance metric. The mean weight coefficients for metrics 1 to 5 are 0.31, 0.14, 0.15, 0.34, and 0.06. Using Equation (10), the comprehensive evaluation metric e for the suspension system's vibration damping performance is obtained. Here, ω_i represents the weight coefficient for each metric, and $\bar{e}_i$ represents the normalized value for each metric. The comprehensive metric value for each test number is ultimately obtained, as shown in Fig 5. The comprehensive metric value for test number 3 is the smallest, indicating that the suspension in test number 3 has the best vibration damping performance among the 27 tests. However, this does not necessarily mean that the suspension system's vibration damping performance is optimal or that the sensitivity of each branch suspension's impact on the overall vehicle vibration damping performance is the best.

$$e = \sum_{i=1}^{5} \omega_i \bar{e}_i \tag{10}$$

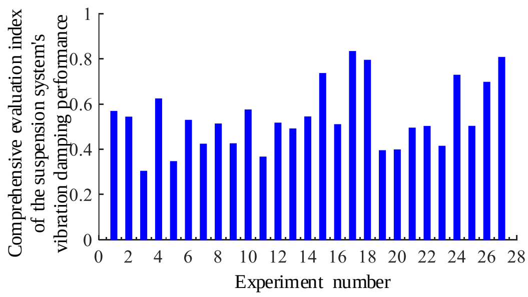

Figure 5: Comprehensive evaluation index of vibration reduction performance

5.4 Grey Relational Analysis

Grey relational analysis targets scenarios with limited samples and numerous influencing factors, refining insights by calculating the grey relational degree between each swing cylinder's initial pressure and the evaluation metrics. This method identifies the optimal experimental combination and the primary and secondary relationships among influencing factors. The steps are: (1)Calculate Grey Relational Coefficients: Quantifies the relationship between each factor and the metrics. (2)Calculate Grey Relational Degrees: Aggregates coefficients to measure each factor's influence. (3)Analyze Grey Relational Degree Response Table: Determines the order of influence based on grey relational degrees, shown in Tab 2. Levels 1, 2, and 3 correspond to initial pressures of 6 MPa, 9 MPa, and 12 MPa in the swing cylinder. The range of grey relational degrees (R) represents the impact variability, with larger R values indicating greater influence.

Tab 2 indicates that the optimal vibration damping performance of the suspension system is achieved when the initial pressures of the swing cylinders are set to 6 MPa, 6 MPa, 6 MPa, 12 MPa, 6 MPa, and 6 MPa, respectively. Among the suspension branches, the second branch has the most significant impact on vibration damping, followed by the first, sixth, third, fourth, and fifth branches, with the fourth and fifth having the least impact. The optimization results presented in Tab 3 are valid only within the tested range. To broaden the application, further predictions and experiments can be made based on the observed trends in factor levels and performance metrics to identify the optimal combination. The experimental results suggest that as the initial pressures of the swing cylinders in the first, second, third, fifth, and sixth suspension systems decrease, the overall vibration damping performance improves, with the first, second, third, and sixth having the most significant effect. Therefore, reducing their pressure values further may enhance performance, if feasible.

Table 2: Grey relational analysis

level	**Factor**					
	A	B	C	D	E	F
1	0.126	0.126	0.121	0.112	0.118	0.122
2	0.110	0.117	0.119	0.118	0.117	0.121
3	0.114	0.107	0.108	0.119	0.114	0.107
R/%	1.60	1.90	1.30	0.70	0.40	1.50
Optimal level	6	6	6	12	6	6
Priority ranking	2	1	4	5	6	3

6. Conclusion

This paper investigates the vibration damping performance of swing cylinder-type hydro-pneumatic suspensions for tracked vehicles. The key conclusions are:

(1)A mathematical model for the suspension's stiffness and damping was developed. Experiments revealed that the initial pressure in the swing cylinder significantly impacts the suspension's stiffness. Experiments showed that vehicle body vibration varies with changes in the initial swing cylinder pressure, and this relationship is not monotonically increasing.(2)Using orthogonal test optimization and grey relational analysis, it was found that the second swing cylinder's initial pressure has the greatest influence on suspension vibration performance, followed by the first, sixth, third, fourth, and fifth in descending order. Lowering the initial pressures of the first, second, third, and sixth swing cylinders improves damping performance. These findings provide a foundation for designing suspension systems in tracked vehicles and for the semi-active and active control of hydro-pneumatic suspensions.

Acknowledgments

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