

NUMERICAL SIMULATION OF PRESSURE PULSATION CHARACTERISTICS OF VIBRATION-REDUCING DRILLING TOOLS

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Abstract: During the drilling process of complex structure wells, the "thrust" problem is encountered, which affects the transmission of WOB. This issue can be addressed by installing a hydraulic oscillator. The pulse generator is the power unit of downhole stimulation tools, represented by the hydraulic oscillator, whose pressure fluctuation characteristics significantly impact the application effectiveness of downhole stimulation tools. This study takes the structure of an interleaved flat blocking valve as the research object and obtains the rotor movement law through theoretical analysis. This law is then imported into Ansys Fluent software platform for secondary development, simulating pressure fluctuation characteristics and influencing factors. The optimal structure under given conditions is determined using orthogonal experimental design method. The results show that pressure wave amplitude has a positive correlation with the eccentricity of the screw rotor, eccentricity of the eccentric hole, and displacement, while having a negative correlation with the aperture of the stator and rotor. As the initial installation angle increases, pressure wave amplitude first decreases and then increases. The primary and secondary relationships of the factors affecting pressure wave amplitude are: aperture of the stator/rotor, eccentricity of the screw rotor, eccentricity of the eccentric hole, displacement, and initial installation angle. This study provides reference for the design and optimization of pulse generators.

Keywords: Pulse generator; Pressure fluctuation; Numerical simulation; Orthogonal experiment

1 INTRODUCTION

Deep land, deep-sea, and unconventional oil and gas resources have become the primary battlefield for oil and gas exploration and development in China. Due to their advantages in oil spill area and spatial utilization efficiency, complex structural wells have developed into the main well type for the development of the aforementioned oil and gas resources. During the sliding directional drilling process of complex structural wells, the high friction between the drill string and wellbore often induces "thrust pressure," preventing effective transmission of weight on bit (WOB) to the drill bit. By installing a hydraulic oscillator to excite axial vibration in the drill string, static friction can be converted into sliding friction, reducing the friction between the drill tools and wellbore, improving the efficiency of WOB transmission, and enhancing control over the tool face [1]. The field application results are significant [2-8].

The disc valve structure of the hydraulic oscillator is its core component. The pressure fluctuation characteristics when drilling fluid flows through the disc valve structure is an important factor affecting the application effectiveness of the hydraulic oscillator. Studies by Yu Changbai et al. examined the impact of the center hole diameter and position of the static valve plate on vibration displacement and velocity [9]; Luo Zhaodong et al. studied the effect of valve port diameter and flow rate on hydraulic oscillator performance [10]; Zhao et al. developed a pressure drop analysis model based on fluid mechanics theory [11]; Li Bin et al. investigated the effects of single-factor vibration characteristics of the hydraulic oscillator on the friction force between the drill string and wellbore [12]; Wu Zhiyong et al. studied the effects of excitation force, vibration frequency, and placement position of the hydraulic oscillator on drag reduction performance [13]; Liu et al. proposed an analytical model to predict the resistance of the drill string under axial vibration caused by the hydraulic oscillator [14]; Shi Xiaolei et al. studied the influence of excitation force form on drag reduction efficiency [15]. However, because the flow through the disc valve structure involves complex turbulent flow, it is difficult to accurately describe its pulsating characteristics using theoretical calculations or 2D numerical simulations, which may result in inaccurate pressure pulsation calculations or excessive pressure loss, thereby affecting the field application of the hydraulic oscillator. Therefore, this paper considers the three-dimensional turbulent characteristics of drilling fluid and analyzes the pressure fluctuation characteristics of the hydraulic oscillator's interleaved flat plate blocking valve and its influencing factors. The orthogonal experimental method is used to select the main control factors, providing a basis for the optimization design of hydraulic oscillators.

2 FINITE ELEMENT MODEL

2.1 Control Equations

For incompressible single-phase fluid, the mass conservation equation and momentum conservation equation are used as the basic control equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \quad (2)$$

Where: ρ is the fluid density, kg/m^3 ; u is the fluid velocity, m/s ; t is time, s ; p is static pressure, Pa ; F_i represents other volumetric forces, N ; τ_{ij} is the stress tensor.

Considering that the fluid is turbulent, the k - ε model is used. The standard k - ε model equations for turbulent kinetic energy k and dissipation rate ε are:

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right) + G_k + G_b - \rho \varepsilon - Y_M \quad (3)$$

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (4)$$

Where: G_k represents turbulent kinetic energy caused by the average velocity gradient, G_b represents turbulent kinetic energy caused by buoyancy, Y_M represents the effect of compressible turbulent expansion on the total dissipation rate.

2.2 Geometric Model and Mesh Generation

A hydraulic oscillator with an outer diameter of 127mm and a displacement of 15L/s is selected. The detailed parameters of the hydraulic oscillator's disc valve structure are shown in Table 1. The disc valve structure consists of a stator, rotor, exit, and inlet, see Figure 1. The main parameters include center hole diameter D , screw rotor eccentricity e , eccentric hole eccentricity E , eccentric hole installation angle θ_1 , rotor rotational speed ω , inlet and outlet length L , stator and rotor thickness l , inlet and outlet diameter d , and displacement Q .

Table 1 Structural Parameters of Hydraulic Oscillator Disc Valve

D/mm	e/mm	E/mm	θ_1/rad	$\omega/(\text{rad/s})$	L/mm	l/mm	d/mm	Q/L/s
30	6	7	1.0472	62.83	200	30	100	15

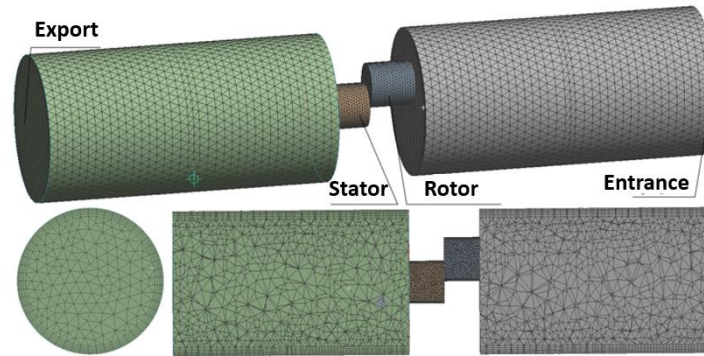


Figure 1 Model of Hydraulic Oscillator

The model is meshed, and the physical preference is set for computational fluid dynamics (CFD). Considering the actual fluid flow situation, adaptive sizing and program-controlled automatic expansion tetrahedral elements are used globally, with a gradual transition, and 5 expansion layers are set at the edges.

A grid independence test is conducted, and the relationship between the grid number and pressure fluctuation amplitude is shown in Figure 2. The outlet and inlet cell sizes are 4mm, and the stator and rotor cell sizes are adjusted to 2mm. The mesh consists of 288,696 cells and 93,084 nodes.

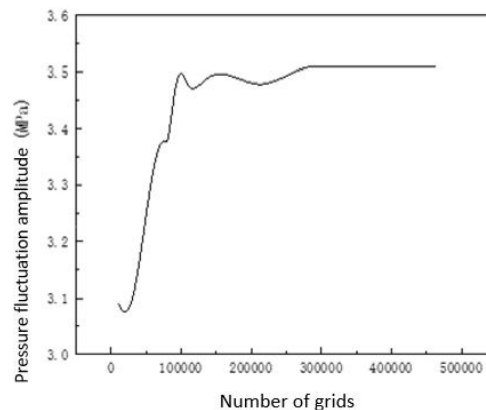


Figure 2 Relationship between Grid Number and Pressure Fluctuation Amplitude

pressure loss. Negative pressure and high-speed jets are generated inside the stator, and significant vortexes are formed at the outlet, which can cause severe erosion to the stator, rotor, and outlet of the disc valve structure. When designing the hydraulic oscillator, optimization of the stator and rotor structures should be considered to extend the service life of the hydraulic oscillator.

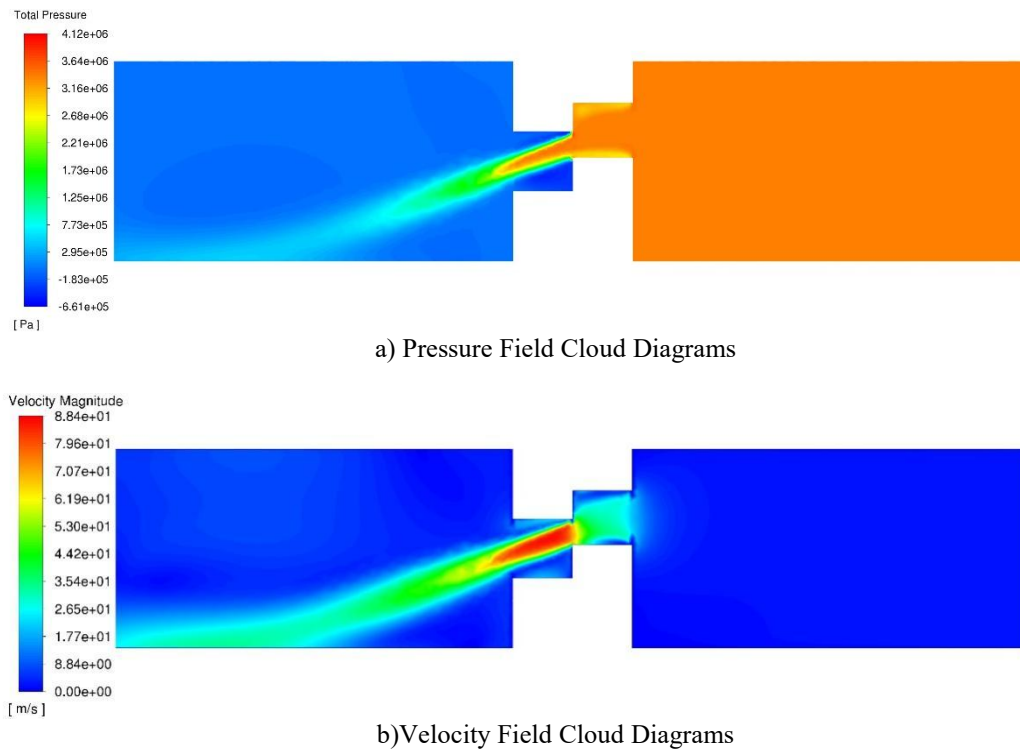


Figure 4 Cloud Map of Pressure Field and Velocity Field

The pressure fluctuation at the inlet approximates a sine wave, ranging from 0.56MPa to 4.05MPa. The pressure loss when the drilling fluid flows through the disc valve structure is approximately 3.49MPa, with the maximum loss being 3.87MPa, which generally meets the field requirement for pressure fluctuation amplitudes of 2-4MPa.

This study considers the influence of three-dimensional turbulent flow on pressure fluctuations, providing a higher level of accuracy. Unlike theoretical calculations, the pressure fluctuation curves generated by numerical simulations show distinct differences in each fluctuation, see Figure 5.

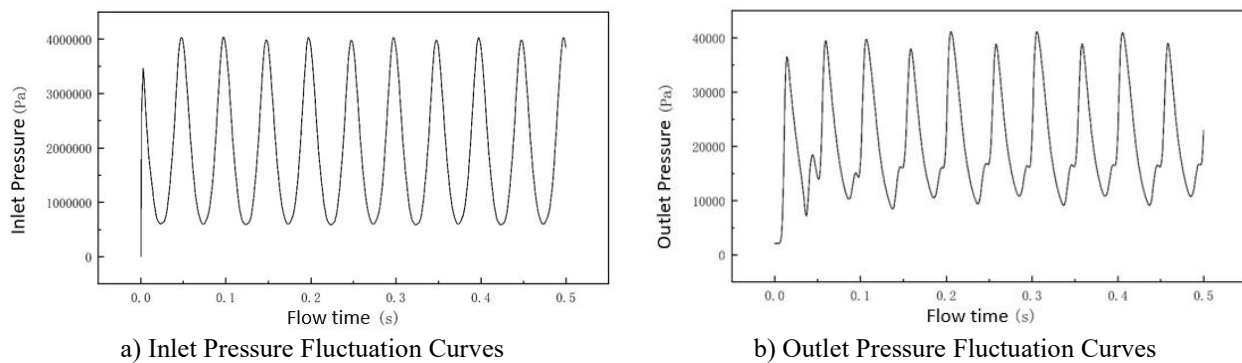


Figure 5 Inlet and Outlet Pressure Fluctuation Curves

2.6 Model Verification

To verify the established model, indoor experimental results from Qian Weiqiang et al. were used [16]. A disc valve model with the same dimensions as the indoor experiment was established. The rotor hole diameter is 0.65 inches, the rotor eccentric hole eccentricity is 0.2 inches, and the stator hole diameter is 0.8 inches. The pressure loss was simulated at flow rates of 0.21, 0.31, 0.40, 0.49, 0.60, 0.70, and 0.79 m³/min. The comparison between the simulation results and the experimental data is shown in Figure 6, which proves the validity of the model.

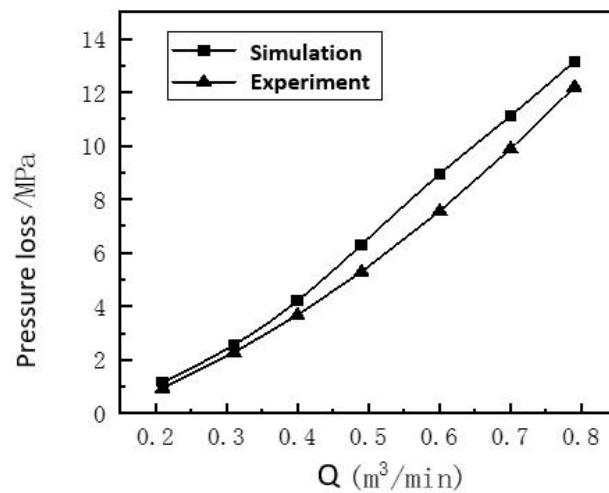


Figure 6 Comparison of Numerical Simulation and Laboratory Experiment Results

3 FACTORS AFFECTING PRESSURE FLUCTUATIONS

Based on the above analysis, factors affecting the flow area include: screw rotor eccentricity e , rotor eccentric hole eccentricity E , rotor eccentric hole diameter D , displacement Q , eccentric hole installation angle θ_1 .

3.1 Influence of Screw Rotor Eccentricity on Pressure Fluctuations

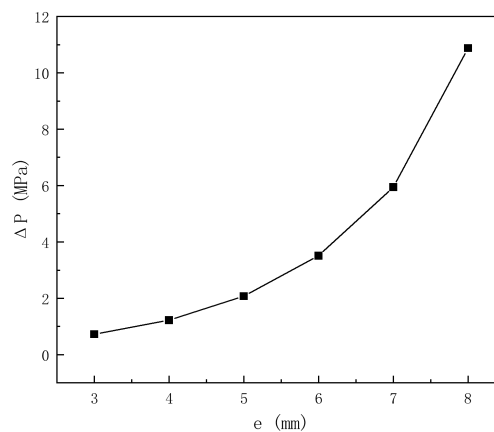


Figure 7 Influence of Screw Rotor Eccentricity on Pressure Fluctuation

The pressure fluctuation amplitude for different screw rotor eccentricities is shown in Figure 7. Pressure fluctuation is positively correlated with e and has a significant impact, with an approximately exponential relationship. When e increases from 7 mm to 8 mm, a 14.286% increase results in an 83.06% change in pressure fluctuation amplitude (from 5.9415 MPa to 10.8766 MPa).

3.2 The Influence of Eccentric Hole Eccentricity on Pressure Fluctuations

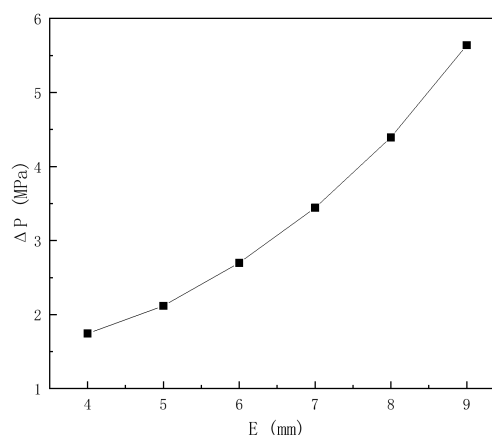


Figure 8 Influence of Eccentric Hole Eccentricity on Pressure Fluctuation

The pressure fluctuation amplitude for different eccentric hole eccentricities is shown in Figure 8. Pressure fluctuation is positively correlated with the eccentricity of the eccentric hole E . Increasing the eccentric hole eccentricity can effectively increase the pressure fluctuation amplitude, although its influence is not as significant as that of the screw rotor eccentricity e .

3.3 Influence of Installation Angle on Pressure Fluctuations

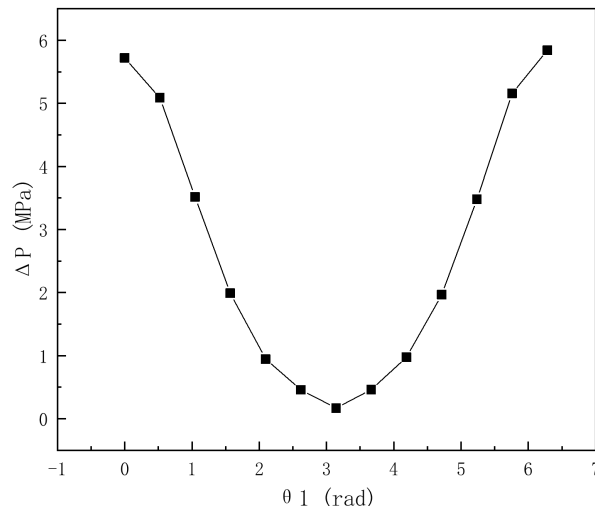


Figure 9 Influence of Initial Installation Angle on Pressure Fluctuation

The pressure fluctuation amplitude for different installation angles is shown in Figure 9. As the installation angle increases, the pressure fluctuation initially decreases and then increases, which is caused by the symmetry of the rotor motion trajectory at different installation angles. The influence of the installation angle on pressure fluctuation is less significant compared to e and E . For example, when the installation angle increases from 30° to 60° (a 100% increase), the pressure fluctuation amplitude only decreases by 30.86% (from 5.0880 MPa to 3.5179 MPa).

3.4 Influence of Pore Size on Pressure Fluctuations

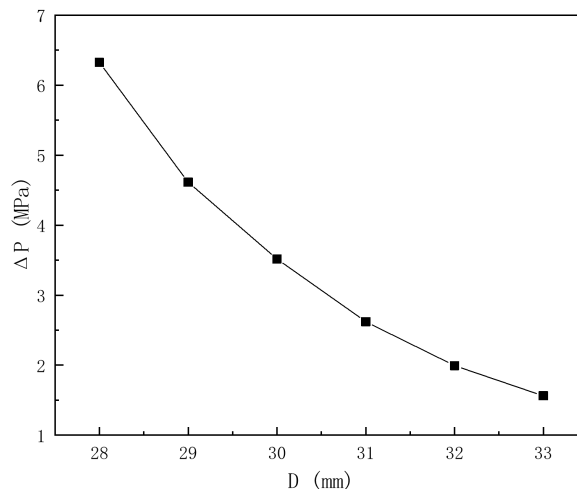


Figure 10 Effect of Pore Size on Pressure Fluctuation

As shown in Figure 10, pressure fluctuation is negatively correlated with pore size, and pore size has a significant impact on pressure fluctuation. For instance, when D increases from 30 mm to 31 mm (an increase of 3.33%), the pressure fluctuation amplitude decreases by 25.48% (from 3.5179 MPa to 2.6214 MPa). This factor should be closely monitored in future experiments.

3.5 Influence of Displacement on Pressure Fluctuations

As shown in Figure 11, pressure fluctuation is positively correlated with displacement. From the trend analysis, it can be observed that the correlation is not as strong as for e and E . After conducting the five sets of single-factor experiments, a preliminary understanding of the influence of different factors on pressure fluctuations is gained, but it is still insufficient for an accurate comparison of the effects of various factors. Therefore, to further explore the influence of different factors, an orthogonal experiment should be designed, and variance analysis and linear regression analysis should be performed.

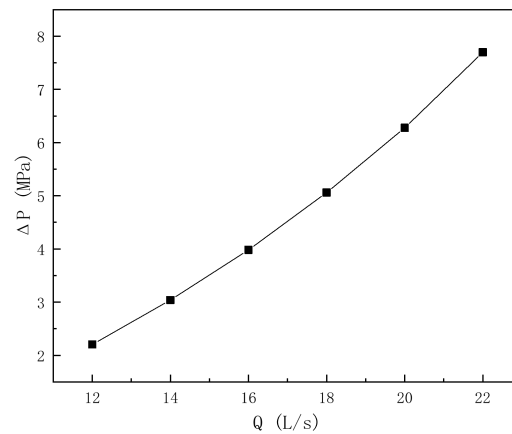


Figure 11 Influence of Displacement on Pressure Fluctuation

4 ORTHOGONAL EXPERIMENT

An orthogonal experimental design is used to explore the influence degree of different factors on pressure fluctuations and to select the main control factors. The $L_{16}(4^5)$ experimental table is used, as shown in Table 2. Numerical simulation experiments are conducted for these parameter combinations, and the results are shown in Table 3.

Table 2 Test Factor Level Table

No.	1	2	3	4	5
<i>F</i> factor	<i>e</i> /mm	<i>E</i> /mm	θ_i /rad	<i>D</i> /mm	<i>Q</i> /L/s
1	5	5	0	28	14
2	6	6	0.5236	30	16
3	7	7	1.0472	32	18
4	8	8	1.5708	34	20

Table 3 Orthogonal Experiment Table

No.	<i>e</i> /mm	<i>E</i> /mm	θ_i /rad	<i>D</i> /mm	<i>Q</i> /L/s	ΔP /MPa
1	5	5	0	28	14	2.8098
2	5	6	0.5236	30	16	2.4557
3	5	7	1.0472	32	18	1.7881
4	5	8	1.5708	34	20	1.1206
5	6	5	0.5236	32	20	3.0785
6	6	6	0	34	18	2.0708
7	6	7	1.5708	28	16	4.0321
8	6	8	1.0472	30	14	3.8077
9	7	5	1.0472	34	16	1.4648
10	7	6	1.5708	32	14	1.3347
11	7	7	0	30	20	19.8641
12	7	8	0.5236	28	18	43.0926
13	8	5	1.5708	30	18	5.2668
14	8	6	1.0472	28	20	31.5447
15	8	7	0.5236	34	14	4.0561
16	8	8	0	32	16	16.8706

Perform a range analysis of the orthogonal experiment. The corresponding results are shown in Table 4.

Table 4 displays the influence levels of five factors—screw rotor eccentricity (*e*), rotor eccentric hole eccentricity (*E*), hole diameter (*D*), eccentric hole installation angle (θ_i), and displacement (*Q*)—on the pressure fluctuation amplitude of the hydraulic oscillator. From Table 4, it can be concluded that the factors, in order of influence, are: *D*, *e*, *E*, *Q*, and θ_i . It is evident that the hole diameter (*D*) has the largest range, making it the most significant factor affecting the pressure fluctuation amplitude. Therefore, when designing the hydraulic oscillator, if the current pressure fluctuation deviates significantly from the target pressure fluctuation, the aperture of the stator and rotor (*D*) and the screw rotor eccentricity (*e*) should be adjusted first to achieve the target pressure fluctuation amplitude, followed by fine-tuning of the other factors. The pulse generator structure combinations with serial numbers 1, 5, 7, and 15 are more reasonable and can be practically applied.

Table 4 Analysis of the Range of Each Factor

Factor	<i>e</i> /mm	<i>E</i> /mm	θ_i /rad	<i>D</i> /mm	<i>Q</i> /L/s
K_1	8.176	12.620	41.616	81.480	12.008
K_2	12.988	37.404	52.684	31.396	24.824
K_3	65.756	29.740	38.604	23.072	52.220

Factor	e/mm	E/mm	θ_i/rad	D/mm	$Q/\text{L/s}$
K_4	57.740	64.892	11.756	8.712	55.608
k_1	2.044	3.155	10.404	20.370	3.002
k_2	3.247	9.351	13.171	7.849	6.206
k_3	16.439	7.435	9.651	5.768	13.055
k_4	14.435	16.223	2.939	2.178	13.902
R	14.395	13.068	10.232	18.192	10.900

To further investigate the impact of different factors on pressure fluctuations, a linear regression analysis was performed on the orthogonal experiment results, as shown in Table 5.

Table 5 Linear Regression Analysis Results (n=16)

	Regression Coefficient	95%CI	VIF
Constant	10.155 (0.335)	-49.324 ~ 69.633	-
e/mm	5.036** (3.321)	2.064 ~ 8.009	1
E/mm	3.729* (2.459)	0.757 ~ 6.701	1
θ_i /rad	-4.949 (-1.709)	-10.626 ~ 0.727	1
D/mm	-2.833** (-3.736)	-4.319 ~ -1.347	1
Q/L/s	1.977* (2.608)	0.491 ~ 3.463	1
Sample Size	16		
R ²	0.803		
Adjusted R ²	0.704		
F value	F (5,10)=8.152, p=0.003		
Dependent Variable: Pressure fluctuation amplitude			
D-W value: 2.840			
* p<0.05 ** p<0.01 (Values in parentheses are t-values)			

The model passed the F-test ($F = 8.152$, $p = 0.003 < 0.05$), indicating that the model is reasonable. The model formula is:

$$\Delta P = 10.155 + 5.036e + 3.729E - 4.949\theta_1 - 2.833D + 1.977Q, \text{ MPa} \quad (12)$$

From the linear regression analysis and orthogonal experiment design results, it is clear that the stator and rotor hole diameter (D) is the most significant factor influencing the hydraulic oscillator's pressure fluctuation amplitude. The screw rotor eccentricity (e), rotor eccentric hole eccentricity (E), and displacement (Q) also have a significant effect on pressure fluctuations, whereas the installation angle (θ_i) has the least impact, see Table 6.

Table 6 The Influence of Different Factors on Pressure Fluctuation

Factor Name	Regression Coefficient Value	p	Influence Relationship
e	5.036	0.008	Significant Positive
E	3.729	0.034	Positive
θ_i	-4.949	0.118	Not Significant
D	-2.833	0.004	Significant Negative
Q	1.977	0.026	Significant Positive

5 CONCLUSION

- (1) The motion trajectory of the dynamic disc valve center hole driven by a single-screw rotor is an ellipse. When the relationship between e , E , and θ_i satisfies a specific equation, the motion trajectory becomes a straight line.
- (2) By considering the three-dimensional turbulent flow of the fluid, more accurate and detailed descriptions of the drilling fluid's pulsation characteristics are achieved, providing a basis for optimizing the design of hydraulic oscillators. Negative pressure and high-speed jets inside the stator, as well as the formation of large vortices at the outlet, can cause severe erosion to the disc valve structure. Thus, optimization of the stator and rotor structures should be considered to extend the operational lifespan of the hydraulic oscillator.
- (3) The average flow velocity at the outlet is significantly higher than that at the inlet, and the formation of large vortices results in pressure losses. The change in flow area leads to changes in velocity and flow patterns, converting the fluid's pressure potential energy into kinetic energy, which is the fundamental cause of pressure loss.
- (4) The hole diameter (D) of the stator and rotor has a significant negative relationship with the pressure fluctuation amplitude. The screw rotor eccentricity (e), rotor eccentric hole eccentricity (E), and displacement (Q) all have a significant positive relationship with pressure fluctuation. The pressure fluctuation amplitude decreases and then increases as the installation angle (θ_i) increases. The influence of factors in order is: $D > e > E > Q > \theta_i$. When designing pulse generators, the aperture of the stator and rotor (D) should be given primary consideration.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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