DESIGN AND PARAMETER OPTIMIZATION OF A SEED STORAGE DEVICE OF A WHEAT PLOT SEEDER
/
小麦小区播种机存种装置的设计与参数优化

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ABSTRACT
To improve the seed separation uniformity in the seed storage device of a wheat plot seeder, this paper investigates the key factors influencing its performance. First, the working principle of the seed storage device and the movement of seeds are analyzed, and the lifting mechanism of the seed storage tube is controlled by an electric pusher. Based on this analysis, the relevant parameter factors are identified. Next, EDEM software is used to simulate the seed storage process and determine the optimal combination of parameters. A three-factor, three-level central composite design experiment is conducted, with the inner diameter of the seed storage tube (D), the lifting height (L), and the lifting speed (V) as the test factors. The coefficient of variation of seed distribution uniformity (m_1) is used as the performance index. The optimal values determined for the parameters are D = 0.06 m, L = 0.015 m, and V = 0.05 m/s. Finally, bench experiments are carried out to verify the results. The experimental findings show that the average coefficient of variation for seed distribution using the traditional lifting lever is 6.46%, while the optimized parameters reduce it to 4.12%, significantly improving seed separation uniformity and meeting the seeding requirements.

摘要
为提高小麦小区播种机存种装置的分种均匀性，对小区播种机存种装置的相关试验因素进行了研究。首先，分析了存种装置的工作原理和种子的运动，通过电动推杆控制存种筒的升降；在此基础上，确定了存种装置的相关参数因素。其次，利用EDEM软件对存种装置进行仿真，以存种筒的内径(D)、上升高度(L)和上升速度(V)为试验因素，以种子分散均匀性变异系数(m_1)为性能指标进行三因素三水平的中心组合设计实验，确定各参数因子的最优组合为 D=0.06m，L=0.015m 和 V=0.05m/s；最后，通过台架实验对优化参数进行了验证。试验结果表明，传统提升杆的平均种子分散均匀性变异系数为 6.46%，而优化参数下的平均种子分散均匀性变异系数为 4.12%，提高了种子分散均匀性，满足播种要求。

INTRODUCTION
Seeds are the fundamental core of agriculture, playing a crucial role in agricultural development. Plot seeding is a key step in the breeding process, and its operational quality directly influences seed selection and breeding outcomes, making it highly significant for food security (*Shang et al., 2021; Zhou et al., 2022; Wang et al., 2022; Feng et al., 2024*). In this context, the wheat plot seeder is a specialized machine used in field experiments to breed high-quality crop varieties. The Austrian company WINTERSTEIGER introduced the world's first plot precision seeder in 1980, which employed suction seeding technology to precisely place individual seeds - an innovation that had a revolutionary impact on agricultural production. As a leading model for plot seeding, the wheat plot seeder performs seeding operations through manual feeding, cone filling, grid tray transportation, seed discharge via the outlet, and distribution using a centrifugal seed divider. Both in China and abroad, plot seeding is commonly conducted using such machines, significantly reducing manual labor requirements (*Cheng et al., 2018; Gao et al., 2022; Okeyo et al., 2020*).

In breeding trials or actual production, it is often necessary to sow multiple crop varieties within a single plot, with each variety requiring a relatively independent and appropriately sized area. The quality of seeding is directly linked to the subsequent growth and development of the crops. Uneven seeding can result in irregular plant distribution within the test plot, thereby compromising the accuracy and reliability of experimental results (*Beckman et al., 2022; Kovács et al., 2023*).

To enhance seeding performance, researchers both domestically and internationally have conducted extensive studies (*Karayel et al., 2022; Yatskul et al., 2018; Zhao et al., 2022; Yuan et al., 2024*).

Gong et al., (2011), proposed an electronic control system for plot seeders and identified the optimal distributor speed for sowing different seed types. *Cheng et al., (2019),* analyzed the effects of three key factors - seed distributor speed, seed separation angle, and seed separation distance - on seeding uniformity, and optimized the corresponding parameters. *Yang et al., (2019),* developed a magazine-type seeding device for plant-row drill planters to address issues of excessive manual labor and low operational efficiency. *Chen et al., (2020),* designed a three-leaf automatic cleaning and seed-changing air-suction seeder for soybean breeding, capable of quickly clearing and replacing residual seeds between plots without requiring machine stoppage. *Liu et al., (2023)*, investigated the forces acting on buckwheat seeds, identifying key influencing factors such as seed displacement, rotation rate, and seed gap layout, and determined the optimal parameter combination through experiments. *Yu et al., (2023),* explored the effects of distributor rotational speed, the number of distributor bosses, and boss length on seeding performance, providing a theoretical foundation for further improvements in seed distributor design. These studies have significantly contributed to enhancing the operational performance of plot seeders. However, uneven seed distribution remains an issue in actual sowing operations, which continues to limit overall work efficiency.

The seeding process initiated by the seed storage device is the first and foundational step in the overall operation of a plot seeder. It plays a critical role in ensuring the effectiveness and uniformity of the entire seeding process. In response to the challenges outlined above, this study focuses on the seed storage device of the plot seeder, aiming to enhance seed distribution uniformity. The findings of this research provide a theoretical and practical foundation for improving the uniformity of wheat seeding in plot trials.

MATERIALS AND METHODS

Structure of seed storage device

The XBJ-150 wheat plot seeder is selected as the research subject, with Figure 1 illustrating the overall machine structure and the configuration of its seed storage device. The seed storage system consists primarily of a seed storage tube and an electric pusher. During operation, wheat seeds are loaded into the seed storage device. The seed storage tube is raised via wireless remote control, allowing the seeds to slide evenly along the conical surface into the slots of the conical lattice disc seed-metering device (*Cheng et al., 2021*). Once all the seeds have been dispensed, the seed storage tube is lowered, again via wireless remote control, until it returns to its original position.

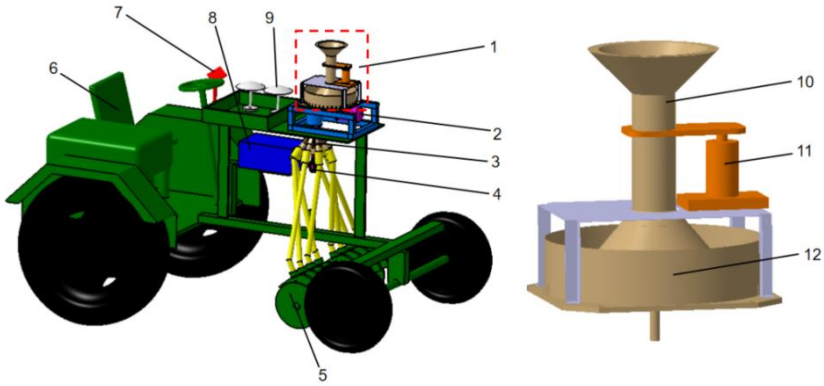


Fig. 1 - Overall structure of the wheat plot seeder and seed storage device structure
1-Seed storage device; 2-Stepper motor; 3-Seed distributor; 4-DC motor; 5-Furrow opener; 6-Operator`s workplace; 7-Human-machine display screen; 8-Controller; 9-BeiDou antenna; 10-Storage tube; 11-Electric pusher; 12-Conical lattice disc seed-metering device

Analysis and determination of experimental factors

As the seed storage tube rises, the wheat seeds slide uniformly into the slots of the conical lattice disc seed-metering device along the cone surface. Figure 2 presents a stress analysis of the forces acting on wheat seeds during their movement along the conical surface. The equations governing this stress analysis are as follows:

$$F_r cos\alpha + \mathrm{mgsin}\alpha - f = \mathrm{m}a_x \quad (1)$$

$$F_r sin\alpha - \mathrm{mgcos}\alpha + F_N = \mathrm{m}a_y \quad (2)$$

where: F_r is the centrifugal force (N); F_N represents the supporting force exerted by the cone on the wheat seeds (N); f is the friction force between the cone surface and the wheat seeds (N); and mg is the gravitational force acting on the seeds (N).

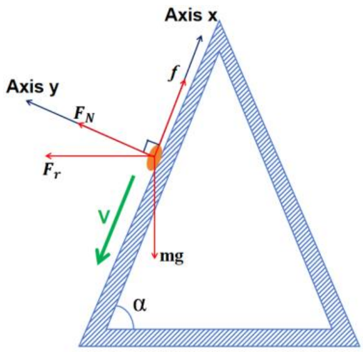


Fig. 2 - Force analysis of wheat seeds moving on the cone

The inner diameter and lifting height of the seed storage tube are key parameters that significantly influence the performance of the seed storage device. The uniform distribution of seeds into the slots of the metering device has a direct impact on seeding quality. The inner diameter of the seed storage tube determines the accumulation height of seeds under a fixed seed quantity. If the diameter is too small, resulting in a high seed accumulation, the vibration-induced adjustment of seed flow is effective. However, excessive seed accumulation can compromise the stability of seed motion when the tube is lifted, thereby negatively affecting distribution uniformity. Conversely, if the diameter is too large and the seed accumulation height is too low, it becomes difficult to generate relative motion within the wedge-shaped slot. This weakens the effect of vibration adjustment, also leading to poor seeding uniformity.

The lifting height of the seed storage tube determines the quantity of seeds that can slide out per unit time once the tube reaches its predetermined height. A smaller lifting height results in reduced seed interference, which can promote stable flow. However, the limited height may also restrict seed movement, increasing the risk of blockage and negatively impacting distribution uniformity. Conversely, when the lifting height is increased, the influence of the seed storage tube on seed flow is reduced, allowing a larger quantity of seeds to be released. However, this also results in a more uniform initial motion state among the seeds, leading to greater mutual interference during descent, which can likewise compromise uniformity.

The lifting speed of the seed storage tube also plays a critical role in maintaining seed distribution uniformity. When the lifting speed is too slow, the seeds remain in contact with the tube for a longer duration, making them more susceptible to interference from the tube wall. This can lead to blockages and uneven seed flow, thereby reducing uniformity. Conversely, if the lifting speed is too fast, the influence of the tube on the seeds is minimized, but the rate at which seeds exit the storage tube increases sharply. This can cause heightened mutual interference among the seeds during their movement, which also negatively affects uniformity.

Therefore, it is necessary to comprehensively consider the influence of the inner diameter, the lifting height, and the lifting speed of the seed storage tube on the uniformity of seed storage to achieve the best seeding effect. The optimal combination of three factors, namely the inner diameter of the seed storage tube (D), the lifting height of the seed storage tube (L) and the lifting speed of the seed storage tube (V), is selected to improve the uniformity of seed dispersion in the slot. According to the structure, working principle and working efficiency of the seed storage device of the wheat plot seeder (*Liu et al., 2010*), it is determined that the diameter of the seed storage tube ranges from 0.04 m to 0.08 m, the lifting height of the seed storage tube ranges from 0.005 m to 0.025 m, and the lifting speed of the seed storage tube ranges from 0.02m/s to 0.08m/s.

Determination of physical characteristics parameters of wheat seeds

The Jimai 22 wheat variety is widely sown in China, especially in northern Anhui. Therefore, the Jimai 22 wheat variety was selected for research. Moreover, 1000 grains are randomly selected and divided into three groups to weigh (W). Then 100 wheat seeds are randomly selected to measure and calculate the average length (l), width (w) and thickness (t), as shown in Table 1.

Table 1

Weight and dimension statistics of 1000 seeds of Jimai 22

Research factor	Group 1	Group 2	Group 3	Average
W/g	44.7	43.8	45.8	44.1
l/mm	6.29	6.39	6.37	6.35
w/mm	3.41	3.38	3.32	3.37
t/mm	3.12	3.16	3.08	3.12

Simulation test
The establishment of simulation model

Based on the results, a three-dimensional model of wheat seeds is established in CATIA software, and the model is imported into EDEM software. Multiple spherical combinations are used to fill the wheat seeds with particles, resulting in the wheat seed model shown in Figure 3.

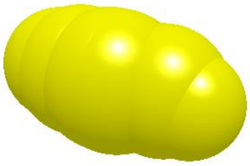


Fig. 3 - Seed model of grain filling

The establishment of seed storage device model

A three-dimensional model of the seed storage device is built by CATIA software and imported into EDEM software, as shown in Figure 4.

Fig. 4 - Model of seed storage device

The inner wall of the seed storage tube is made of resin, and the surface cone of the conical lattice disc seed-metering device is made of steel. The parameters of seed, resin and steel obtained through literature search and calculation are shown in Table 2 (*Li et al., 2018; Zhu et al., 2019; Diao et al., 2024)*.

Table 2

Relevant parameters of simulation model

Relevant parameters	Seed	Resin	Steel
Poisson's ratio	0.29	0.39	0.3
Shear modulus /Pa	5.01e+8	7.19e+8	7.00e+10
Density /(kg·m^{-3})	1350	1240	7800
Relevant parameters	Seed	Resin	Steel

The parameters of the contact relationship between steel and the wheat seed and between resin and the wheat seed are shown in Table 3.

Table 3

Contact parameters between materials in the simulation model

Contact parameters	Seed-seed	Resin-seed	Steel-seed
Recovery coefficient	0.50	0.50	0.60
Coefficient of static friction	0.58	0.20	0.50
Coefficient of dynamic friction	0.08	0.02	0.01
Contact parameters	Seed-seed	Resin-seed	Steel-seed

Experimental design

According to the three factors obtained in Section 2.2, the optimal parameter combination is obtained using the three-factor and three-level orthogonal test method with the seed scattered uniformity coefficient of variation (m_1) as the evaluation index (*Liu, 2011)*. The seed scattered uniformity coefficient of variation (m_1) can be calculated as:

$$m_1 = \frac{\sqrt{\sum_{i=1}^{n}(M_i - \sum_{i=1}^{n} M_i/n)^2/(n-1)}}{\sum_{i=1}^{n} M_i/n} \tag{3}$$

where i represents the number of the slot of the conical lattice disc seed-metering device; M_i denotes the seed quality in slot number i; n represents the number of slots, n=40.

The relevant parameters of the simulation model are set. Seeds are added into the seed storage tube and an orthogonal experiment is conducted with a designed seed quantity of 0.15 kg.

Table 4 presents the factor level encoding table.

Table 4

Table of factor levels for orthogonal tests

Encoding	D/m	L/m	V/(m/s)
+1	0.04	0.005	0.02
0	0.06	0.015	0.05
-1	0.08	0.025	0.08

After the simulation seeding experiment is completed, the *Analyst Tree* interface is used to generate a grid group in each slot of the conical lattice disc seed-metering device. This allows for the measurement of wheat seed mass in each slot and the calculation of the seed distribution uniformity coefficient of variation, as shown in Figure 5.

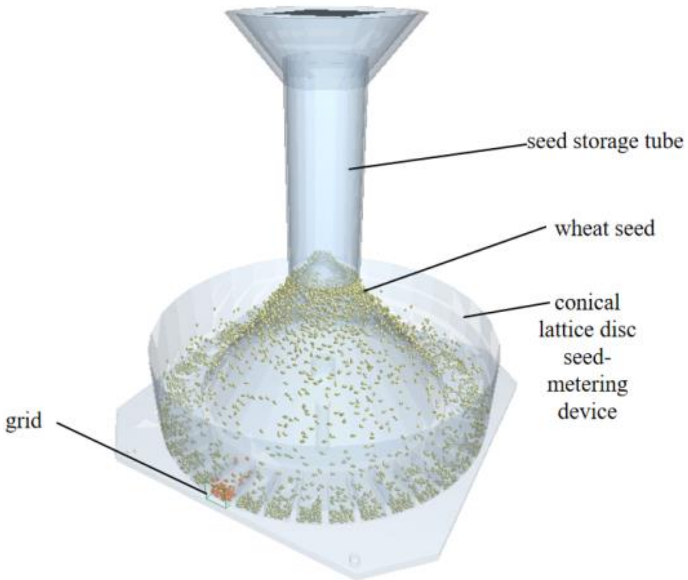


Fig. 5 - The diagram of the simulation experiment

Bench test

To verify the effectiveness of the optimal parameters, the seed storage device is improved according to the optimal parameters analyzed in the previous section. The original lifting lever is replaced with an electric pusher and compared with the traditional lifting lever. Eight sets of tests are conducted on the JPS-12 seed planter performance test bench in the Intelligent Agricultural Machinery Equipment Engineering Laboratory of Anhui Agricultural University, and the seed scattered uniformity coefficient of variation is calculated, as shown in Figure 6.

Fig. 6 - The diagram of the bench test

RESULTS

Simulation test results

The seed scattered uniformity coefficient of variation in the orthogonal test is shown in Table 5.

Table 5

Statistics of coefficient of variation of orthogonal test

Number	D/m	L/m	V/(m/s)	m_1/%
1	0.04	0.005	0.05	5.87
2	0.06	0.015	0.05	3.62
3	0.06	0.025	0.02	5.67
4	0.06	0.015	0.05	3.05
5	0.08	0.015	0.08	5.98
6	0.06	0.005	0.02	5.08
7	0.04	0.015	0.08	5.24
8	0.08	0.005	0.05	4.65
9	0.08	0.025	0.05	5.84
10	0.06	0.015	0.05	3.46
11	0.04	0.025	0.05	3.87
12	0.08	0.015	0.02	4.43
13	0.06	0.005	0.08	4.98
14	0.04	0.015	0.02	5.67
15	0.06	0.025	0.08	6.01
16	0.06	0.015	0.05	3.97
17	0.06	0.015	0.05	3.34

According to the simulation results in Table 5, the average of m_1 (μ) is calculated as 4.749%, and the standard deviation (σ) is 0.998%, so the standard deviation ranges, μ±σ, μ±2σ and μ±3σ, are [3.742%, 5.747%], [2.744%, 6.745%] and [1.746%, 7.743%], respectively. That is, when the three factors are orthogonally combined at the three levels, the probabilities of m_1 within the above three intervals are approximately 68%, 95% and 99.7%. Design Expert 13 software (DSP 13) is used to analyze the simulation data, and the dimensionless factor encoding regression equation was obtained as follows:

$$Y_1=3.49-0.2187X-0.0238Y+0.045Z+1.05XY+0.745XZ -0.61YZ+0.7323X^2+1.09Y^2+1.36Z^2 \quad (4)$$

where X represents the inner diameter of seed storage tube. Y denotes the lifting height of the seed storage tube. Z represents the lifting speed of the seed storage tube.

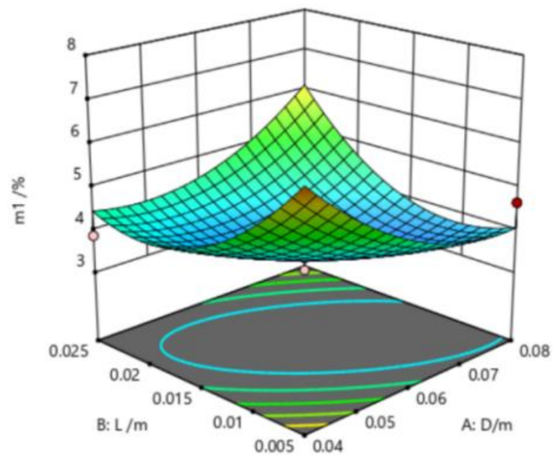
The regression equation analysis is shown in Table 6, and the coefficient of variation model is highly significant (P<0.01), with a mismatch term of P=0.3822>0.05, indicating that the regression equation is well fitted. According to Table 6, the influence of each experimental factor on the coefficient of variation, in descending order, is as follows: the height of the seed storage tube, the inner diameter of the seed storage tube and the speed of the seed storage tube.

Table 6

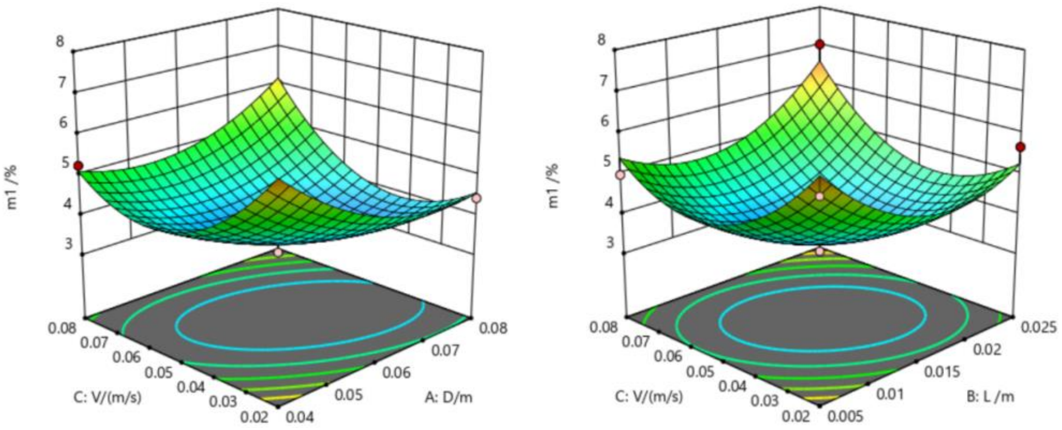
Statistics of coefficient of variation of orthogonal test

Source	Sum of Square	Freedom	Mean Square	F	P
Model	31.23	9	3.98	11.41	0.004
X	3.28	1	3.28	11.13	0.0063
Y	3.85	1	3.85	12.56	0.0054
Z	2.13	1	2.13	6.43	0.0318
XY	1.73	1	1.73	5.13	0.0382
XZ	0.35	1	0.35	1.06	0.3223
YZ	0.23	1	0.23	0.52	0.4747
X^2	11.32	1	11.32	50.45	0.0029
Y^2	6.46	1	6.46	21.55	0.0004
Z^2	3.11	1	3.11	6.34	0.0257
Residuals	3.87	11	0.33		
Lack of Fit	2.22	4	0.42	1.63	0.3822
Pure Error	2.23	7	0.29		
Cor Total	35.1	20			

Figure 7 displays the influence of various factors interacting with each other on the coefficient of variation (m_1). Figure 7a shows the effect of L and D on the coefficient of variation. When L is constant, with the increase of D, m_1 decreases first and then increases. When D is constant, with the increase of L, m_1 decreases first and then increases. Figure 7b shows the effect of V and D on the coefficient of variation. When V remains constant, with the increase of D, m_1 decreases first and then increases. When D remains constant, with the increase of V, m_1 decreases first and then increases. Figure 7c shows the effect of V and L on the coefficient of variation. When V is constant, with the increase of L, m_1 decreases first and then increases. When L is constant, with the increase of V, m_1 decreases first and then increases.



(a) The impact of L and D on m_1



(b) The impact of V and D on m_1 (c) The impact of V and L on m_1

Fig. 7 - The influence of the interaction of various factors on the coefficient of variation

The regression equation for the impact of significant factors on the seed scattered uniformity coefficient of variation is as follows:

$$m_1=26.88-371.28D-744.46L-254.58V+5237.5DL+1241.67DV+2033.33LV+1380.625D^2+10872.5L^2+1830.625V^2 \quad (5)$$

Using the objective function m_{1min}, the optimal parameter combination was determined through optimization in MATLAB/Simulink. The resulting optimal values for the three factors are: inner diameter D=0.06 m, lifting height L=0.015 m, and lifting speed V=0.05 m/s.

Bench test results

Table 7 displays the results of the comparative experiment between the traditional lifting lever and the electric pusher, which indicates that the average scattered uniformity coefficient of variation for using traditional lifting levers is 6.46%, and for using the electric pusher, it is 4.12%. Compared to traditional lever lifting, the improved method significantly improves the uniformity of wheat seeds and meets operational requirements, which proves the feasibility of the optimal parameter combination.

Table 7

Result of the bench test

Number	m_1/%	
	Before optimization	After optimization
1	5.61	4.58
2	6.94	3.66
3	6.64	3.89
4	5.71	5.13
5	6.44	3.61
6	6.39	3.16
7	7.17	4.28
8	6.82	3.77
Average	6.46	4.12

CONCLUSIONS

(1) Taking the seed storage device of the wheat plot seeder as the research object, the working principle and experimental factors related to the seed storage device are analyzed. An electric pusher is used instead of a traditional lifting lever to control the lifting of the seed storage tube. And the experimental factors related to the seed storage device are determined, namely the inner diameter of the seed storage tube (D), the lifting height of the seed storage tube (L), and the lifting speed of the seed storage tube (V).

(2) Through analysis, the ranges of the test factors are determined to be [0.04 m, 0.08 m], [0.005 m, 0.025 m] and [0.02 m/s, 0.08 m/s], respectively. A three-factor and three-level simulation experiment is conducted with the seed scattered uniformity coefficient of variation as the performance index. It is determined that the influences of each test factor on the coefficient from large to small are L, D, and V, and the optimal solution of experimental parameters is determined to be D=0.06 m, L=0.015 m, and V=0.05 m/s.

(3) Under the verification test, the range of the seed scattered uniformity coefficient of variation is [3.16%, 5.13%], with an average value of 4.12%. Compared with the traditional lifting lever, its coefficient of variation is reduced by 2.34%. Under the optimized combination of working parameters, the device achieves a relatively high working performance.

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